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CONTENTS.

	PAGE
THE MAGNAVOLT EXCITER—A ROTATING AMPLIFIER	71
THE APPLICATION OF THE MAGNAVOLT	76
TYPE OLX AIR-INSULATED METAL-CLAD SWITCHGEAR	82
"ENGLISH ELECTRIC" COLD ROLLING MILL PLANT IN A SCOTTISH ALUMINIUM WORKS	90
PRESSURE CHARGING THE FOUR-STROKE DIESEL ENGINE	98

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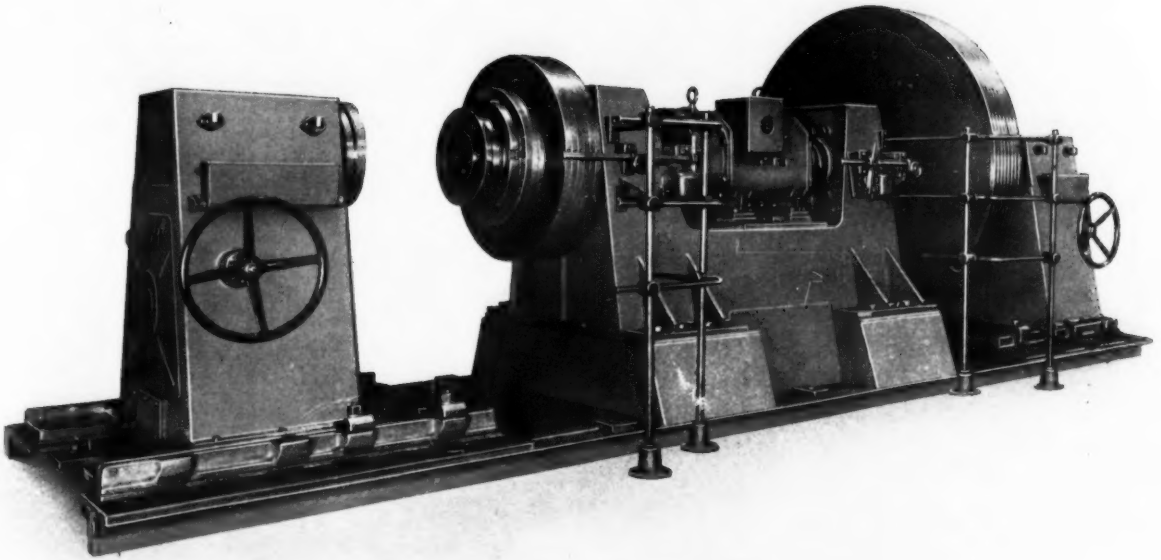


An 8-ton 1,000 r.p.m. flywheel set and driving motor, controlled by magnavolt exciter (not shown).

The English Electric Journal

Vol. XI. No. 3 MARCH, 1950. One Shilling

The Magnavolt Exciter—A Rotating Amplifier

By E. A. BINNEY, Chief Engineer, Traction Machine Development, Bradford.

The rotating amplifier type of direct current generator has, in recent years, gained a prominent position in the control of electric machines. The English Electric Company has been in a position to provide a suitable machine since the earliest days of such applications and has originated machines of this type which have been in highly successful operation over a number of years.

Rotating amplifiers developed by The English Electric Company fall into two distinct groups :—

(*a*) The single-stage or tuned field type (" SS " type).

(*b*) The multi-stage type (" RR " type).

The " SS " Type Magnavolt Exciter.

The first mentioned, single-stage amplifier, works on the principle of matching the resistance line with the slope of the saturation curve on the non-saturated portion as shown in Fig. 1.

The Company has used machines embodying this principle in a number of applications, the exciter being referred to as the " SS " exciter, derived from the inherent " speed sensitive " characteristic of the machine ; that is, a relatively constant speed drive is desirable to obtain consistent results, since the resistance line is perfectly matched for a given speed only. The " SS " exciter is a normally constructed direct current machine having either a self-exciting shunt field or series field and additional fields known as " reference " fields and " control " fields.

Fig. 2 shows a diagram of connections in which a shunt field S is used ; a tuning resistance T is provided to enable the resistance in the field circuit to be adjusted so that the resistance line B in Fig. 1 lies substantially on or slightly above the straight portion of the saturation curve A. With no current flowing in fields R and C, the machine will not build up. When, however, a very slight additional excitation is provided, as indicated by S in Fig. 1, the machine will build up to a value A_1, being the point of intersection of a line B_1, through S, parallel to the resistance line B.

In the practical application of this machine, the ampere turns S are provided either by a

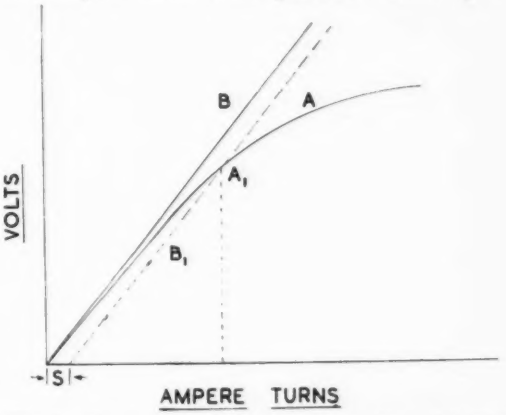


Fig. 1.—Curve showing principle of operation of " SS " type magnavolt exciter.

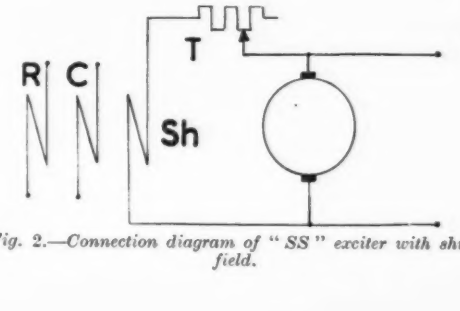


Fig. 2.—Connection diagram of " SS " exciter with shunt field.

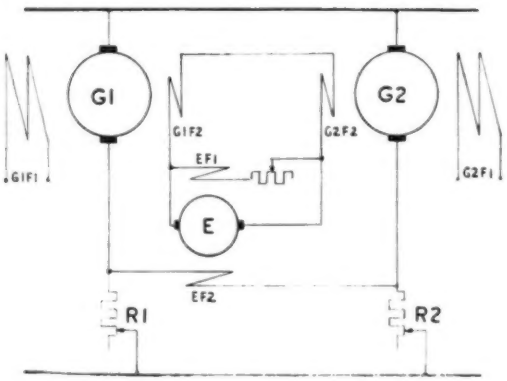


Fig. 3.—Application of "SS" type magnavolt exciter for balancing current from two generators.

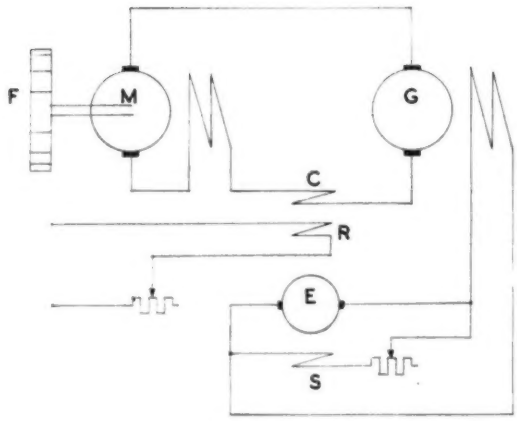


Fig. 4.—Scheme for controlled acceleration of flywheel.

single control field C (Fig. 2) connected to an external source of supply, such as a bridge circuit, or a second field R is provided, termed "reference" field, which when excited produces an m.m.f. in opposition to the m.m.f. of the control field.

Fig. 3 shows an application of the "SS" type magnavolt for balancing the current from two supply generators in which a single control field is used. The two generators G1 and G2, which may be quite dissimilar in characteristics and output, are provided with shunt fields G1F1, G2F1, and small auxiliary fields G1F2, G2F2. The latter are excited by the relatively small "SS" exciter E, the sense of the supplementary excitation of fields G1F2 and G2F2 being reversed, so that machine G1 may have an increased excitation due to field G1F2, while machine G2 has a reduced excitation due to field G2F2. The output current flows through resistances R1 and R2 respectively. The control field EF2 is connected between the inner terminals of these resistances and ensures a correct sharing of the load, since any unbalance in voltage will result in field EF2 being excited with resulting correcting action by exciter E.

Fig. 4 shows in principle a scheme using both a reference field R and a control field C, the application being one in which a flywheel F is accelerated at a desired rate to a given speed. In this case the reference field is excited from a constant source of supply. The control field carries the current supplied by generator G, and the exciter supplies current to the generator field.

When motor M is stationary, the initial excitation caused by exciter E in response to the pre-excited field R causes a current to flow in the main circuit through control field C. The difference of the m.m.f. of fields C and R (which oppose each other) is initially very small, since the voltage required from the generator G need only overcome the ohmic drop in the circuit. Obviously any tendency for a greater current to flow than the value established by the pre-setting of the reference field would result in the swamping of the latter by the control field, hence the resultant ampere turns equivalent to S in Fig. 1 would disappear and the exciter could not build up.

Acceleration takes place at substantially constant current, the generator voltage increasing linearly. When the desired speed is reached, the accelerating current can be reduced to zero by merely opening the reference field circuit. Controlled braking action can be effected by reversal of the reference field current.

A practical development of this application is shown in the illustration on the frontispiece. This illustrates an 8-ton 1,000 r.p.m. flywheel set and its driving motor supplied to the British Belting & Asbestos Company. The magnavolt exciter and supply generator are not shown.

If the exciter is provided with a series field it acts as a series generator, and the tuning resistance is placed in the load circuit.

Fig. 5 shows a schematic diagram for an "SS" exciter used in connection with a generator regulated for constant voltage. The tuning resistance must, in this case, carry the full exciter output current. If the reference field R is supplied from a constant voltage supply, the voltage of the generator G will be established at a value pre-determined by the windings R and C as previously pointed out.

In referring to Fig. 1, it will be obvious that the value of S required to cause the resistance line B to intersect a point on the straight line of the curve, can be reduced to a very small value by careful tuning, i.e., the aligning of B relative to the straight part of A. The amplification may be therefore very high when expressed as the ratio $\frac{AT}{S}$ where AT is the value of ampere turns for a given voltage and S the balance of the opposing m.m.fs where two fields are provided or alternatively the actual m.m.f. of a single control field.

In the " SS " exciter, the reference and control fields are obviously in the same magnetic circuit as the main or self exciting fields. Hence there is bound to be an inductive relationship between the windings which causes a slowing up of any change in flux, and consequently a less rapid response to a change in the control m.m.f. In many applications, the rate of response obtained is satisfactory and machines operating on the same principle have been used extensively in the United States.

The " RR " Type Magnavolt Machine

It was early recognised that the limitations of the " SS " exciter, with its mutually inductive control and power circuits, could be overcome by arranging these circuits so as to avoid mutual inductance. Thus any change in the control flux could take place without damping action due to the power circuit windings. It was further realised that the speed sensitivity of the " SS " machine might be a handicap in many applications. Hence in avoiding this limitation a wider scope of application could be attained. The result of this analysis led to the development of the " rapid response " type magnavolt, briefly designated the " RR " type machine. This is essentially a two-stage rotary amplifier.

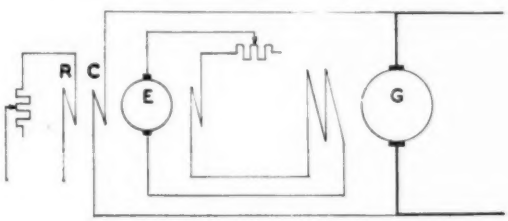


Fig. 5.—Typical schematic diagram for " SS " exciter used to regulate generator for constant voltage.

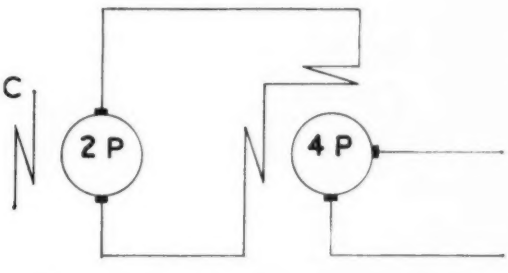


Fig. 6.—Diagram of " RR " 2-4-pole arrangement for two-stage amplification.

The English Electric Company has had " RR " type magnavolt machines in service for a number of years. The reliability and adaptability of this machine has therefore been well established. As the machine is of a novel design, a description may be of interest.

As pointed out in connection with the " SS " type machine, mutual inductive relationship of the control and main exciting windings results in delayed response to a change in the control circuit. In the " RR " (for rapid response) machine, the control circuit is magnetically and electrically distinct from the main magnetic and electric circuits. This is effected by providing two armature windings of p and 2p polar distribution and corresponding sets of field coils, the number of actual pole pieces being 2p. In the smaller size machine the number of poles used is two and four. The armature windings occupy the same slots, each having its own commutator and brush gear, the commutators being placed at opposite ends of the core. The poles are provided with independent coils forming the main and control exciting fields. The magnetic circuit is laminated throughout.

Fig. 6 shows a typical schematic diagram of a 2-4-pole arrangement in which the 2-pole circuits are used as the first stage amplification and the 4-pole circuits as the second stage amplification. The control field C, as actually carried out, comprises four field coils, two of which provide North poles and two of which provide South poles, as shown in Fig. 7*a*, while the 4-pole field coils are arranged in the conventional manner so as to produce successive North and South poles, as shown in Fig. 7*b*. The 2-pole armature output is used to excite the 4-pole system (see Fig. 6).

The 2-pole armature windings embrace two mechanical pole arcs, hence the 4-pole magnetic flux cannot generate a voltage in the 2-pole armature, while the two adjacent poles of equal polarity generate a voltage proportional to their excitation.

The 4-pole armature winding is in the same way only responsive to the 4-pole magnetic system, so that each armature winding acts in response to the corresponding magnetic system as if it

were entirely independent.

Any change in the excitation of the control field C (which produces the magnetic system Fig. 7*a*) will be uninfluenced by the presence of the 4-pole fields, since the mutual inductance of the 2-pole and 4-pole coils occupying one pole body is in the opposite sense to that of the coils on the next pole.

There is a magnetic unbalance, as shown in Fig. 8, which is of no consequence dynamically on small machines and can be avoided on large machines by adopting a 4-8-pole arrangement.

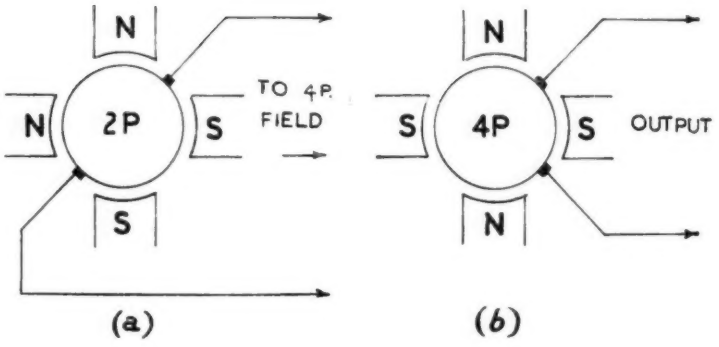


Fig. 7 (a and b).—Field polarity of 2-4-pole arrangement in Fig. 6. (a) Control field C. (b) 4-pole field.

Fig. 8 shows the actual effect on the flux distribution in the superimposed 2- and 4-pole field system. M represents the 4-pole m.m.f. produced by the control field m.m.f. m. The chain dotted lines show that poles 1 and 4 have augmented m.m.f., while poles 2 and 3 have reduced m.m.f. In the non-saturated portion of the saturation curve, this displacement of m.m.f. will not reduce the actual 4-pole magnetic flux since the m.m.f. per pole pair remains constant.

It will be obvious that the " RR " type exciter provides a means of obtaining a rapid response at the output terminals, i.e., the 4-pole armature. At the same time it provides a two stage amplification in a simple manner.

The use of separate armature windings has the advantage that the commutation problem is simplified ; the first stage commutator, which deals with low power, is uninfluenced by the load conditions under which the second stage output commutator operates, hence the possibility of the exciting circuit being affected by poor surface conditions, bad brush contact, etc., is for all practical purposes eliminated.

On the other hand the output commutator operates under entirely normal conditions, the commutator problem being that of any conventional machine of the same rating, and in practice has been proved to give entirely trouble-free operation.

In the case of the " SS " type magnavolt exciter, the amplification factor under static conditions was shown to be very favourable while obviously it is sensitive to speed and temperature variation, since the alignment of the resistance line B is entirely dependent on speed and resistance.

The " RR " type magnavolt exciter is dependent on speed only in that the voltage generated in both windings is proportional to speed and magnetic flux. For a given flux in the first stage magnetic circuit, the first stage amplification is proportional to speed and the overall amplification is proportional to the square of the speed, since the main flux is itself proportional to the speed. It is therefore advantageous to operate the " RR " magnavolt exciter at reasonably high speeds in order to get the greatest amplification and rate of response. A change in speed during its normal operation is, however, quite admissible and this machine can be depended on to give satisfactory control while compelled to operate over quite a wide range in speed, provided the lowest operating speed is initially allowed for in the design.

An application of this nature is for instance one in which the machine is used for controlling the battery charging current from a generator operated by a variable-speed diesel engine, as in a locomotive drive. A change in sensitivity will occur, but will only reduce the accuracy of the control.

In its simplified form, shown in Fig. 6, the

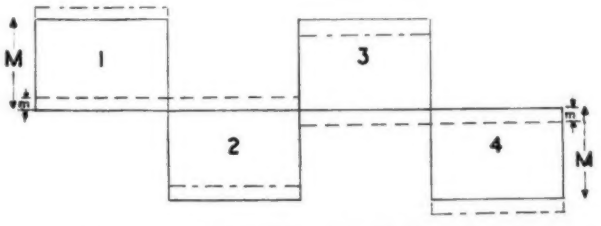


Fig. 8.—Flux distribution in superimposed 2- and 4-pole field system.

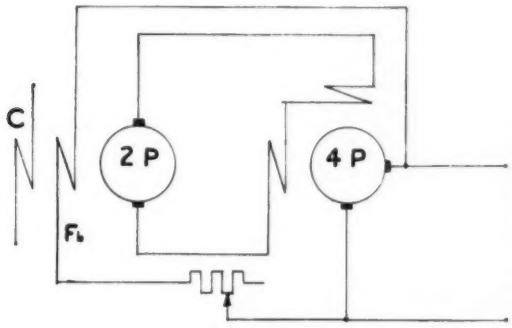


Fig. 9a.—Connections of shunt fed positive feed-back field.

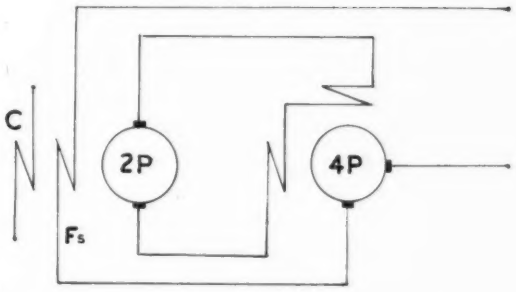


Fig. 9b.—Output current used for series connected positive feed-back.

magnification obtained depends upon the design factors of the machine. If for instance the energy required to excite the field coil C, such that the resultant voltage across the brushes of the 4-pole armature reaches a maximum straight line value (i.e., below the saturation knee), is 1 watt and the output at the maximum voltage is 3,000 watts, then the magnification factor is 3,000.

The degree of magnification obtainable naturally depends upon the speed and size of the machine, and the above values merely indicate the magnification obtained in a particular case. Other factors usually limit the degree of amplification to values considerably below the maximum obtainable with a magnavolt machine, the rapidity of response required having an important bearing on the degree of utilisation of the magnification. The simplicity of design of the magnavolt machine is particularly suited to the introduction of means for increasing or decreasing the magnification and rate of response in relation to changing load conditions.

As the voltage of the 4-pole armature is directly proportional to the applied exciting current in the 2-pole control field, it is obvious that the latter can be supplemented by a field winding Fb (Fig. 9a), excited from the 4-pole brushes, carrying the required ampere turns provided from the 4-pole output circuit.

In some applications the current supplied into the output circuit can be used to excite a suitable series winding Fs (Fig. 9b) in the 2-pole circuit.

When a reference field is provided, the same effect can be obtained by biassing this field R (Fig. 9c) by means of a voltage component from the output circuit. By such means the magnification factor can be greatly increased. Naturally the stability of the system is reduced.

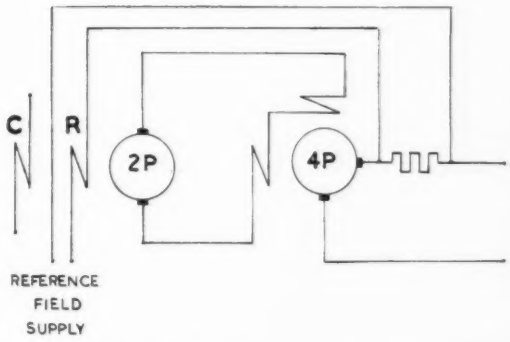


Fig. 9c.—Use of a shunt in output circuit to provide positive feed-back.

The conflicting requirements of stability and magnification are continually confronting the engineer in the application of rotary amplifiers. In the magnavolt exciter, increased magnification is possible by means of external adjustments of the biassing circuits so that the inherent characteristics of the machine are initially independent of this feature, which is a distinct advantage as it allows for final adjustment to be made after installation of the equipment.

It is possible to introduce further windings in the 2-pole magnetic circuit for providing control circuits modifying the output characteristics of the magnavolt exciter in accordance with speed or other functions of the controlled machine.

The magnavolt exciter may also be so controlled that under certain load conditions the stability feature is emphasised, while under other conditions the high magnification factor is developed to the best advantage. An arrangement of this type is particularly advantageous

in the load control of a diesel electric generator scheme in which the magnavolt exciter controlling the generator excitation is adapted to give a relatively slight response as long as the governor acts to vary the fuel supply, while responding to a much closer degree to engine speed variation when the fuel supply is at its maximum.

There are many applications in which this useful machine may be successfully employed. Some of these applications are described in a separate article in this issue of "The English Electric Journal."

The Application of the Magnavolt

By A. ASBURY, B.Sc., A.M.I.E.E.,
Special Engineering Section, Stafford.

In the past fifteen years there has been a great increase in the use of automatic controls to save man-power and obtain features which are not possible by manual control. The magnavolt exciter described in the previous article is a very useful component in such controls due to its unique combination of properties.

Properties of the Magnavolt.

It is a robust and reliable machine which requires no unusual attention. Its principle of operation is simple and offers little difficulty to the maintenance engineer. These characteristics make it very suitable for applications in which continuity of service is essential.

The ease with which the magnavolt can be made responsive to a combination of signals enables complex controls to be carried out with a minimum of components—especially contactors. This also enables load limiting circuits to be employed, so preventing damage to the equipment due to maloperation.

The high amplification available in the magnavolt allows small power control circuits to be employed and gives the maximum economy in components. Further, the accuracy of the control can meet normal industrial requirements and give ample margin for rapid response.

The magnavolt is not limited in size by design considerations within the range encountered in control schemes. It can, therefore, be built to do excitation direct where electro-mechanical regulators would need an exciter.

The Form of Control Circuits.

Control circuits can be divided in two groups —open and closed. The open controls are used where accuracy is not important and disturbing factors such as load or temperature change are predictable. An example is the simple Ward-Leonard control of speed with a manually-operated rheostat.

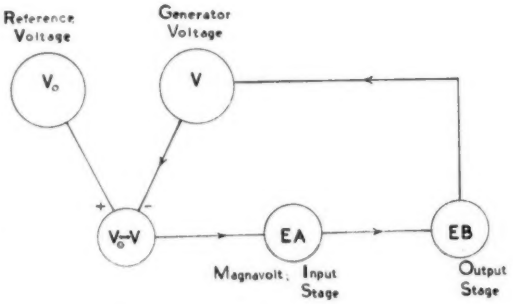


Fig. 1.—Basic closed system control.

Where greater accuracy is required or disturbances are unpredictable, it is necessary to have a system of control which will counter the effect of the changes. Such systems are invariably closed controls in which the difference between the desired and the actual quantity to be controlled, is used to make the necessary correction. This is shown in schematic form for a voltage control in Fig. 1. The difference between the reference voltage V_o and the actual generator voltage V is amplified through the two stages of the magnavolt EA and EB and used to control the generator excitation.

The reason for the term "closed" system will be evident from this diagram and its function can be visualised by considering what happens when, for some reason, the voltage changes. Suppose that the voltage falls, due to increase in load. Then the difference V_o-V increases,

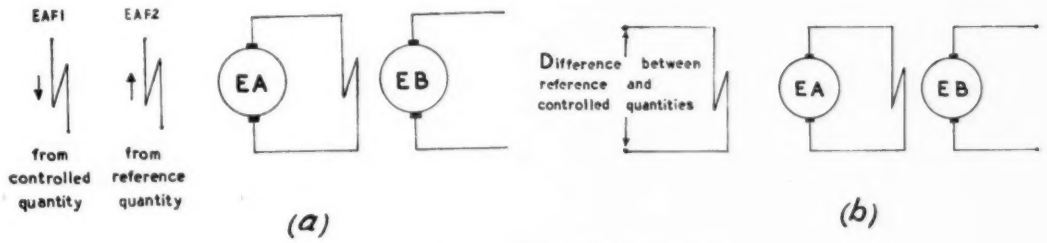


Fig. 2 (a) and (b).—Arrangement of input circuits.

increasing in turn the excitation applied to the input stage of the magnavolt, then the output stage of the magnavolt and finally the excitation of the generator. In this way the generator voltage is brought back to a value very near V_0.

Two essential features of this system will be apparent ; first the reference voltage and secondly the fact that a small difference from the reference is necessary for the functioning of the control. In these features lie the limits of the accuracy of the control scheme. Evidently the reference must always be maintained within narrower limits than are required in the complete control. The difference from the reference is kept small by the high amplification of the magnavolt which enables the full generator excitation to be produced for a very small input signal.

Comparison Circuits for Various Types of Control.

In general two arrangements are possible, either making the comparison in the magnavolt input stage or in the external circuits. These are shown in general in Fig. 2 (a) and (b). The first arrangement is most flexible but does not give the maximum amplification available. The second requires larger units in the control circuits but gives the maximum amplification. Examples of the application of these principles to a speed and a D.C. voltage control are given in Figs. 3 and 4.

An interesting modification is possible where the reference is replaced by an inherent property of the input circuits as in the A.C. voltage regulator which uses the "intersecting impedance network" (Fig. 5). The magnavolt input has two opposing fields, one carrying the current through a resistance and the other the current through a saturating reactor. At equilibrium the ampere turns of field F1 will be slightly larger than those of F2 and this excess, amplified by the magnavolt, will supply the excitation of the generator. It will be seen from Fig. 5 (b) that if the voltage tends to increase, the reactor current increases more rapidly than the resistance current and the difference in ampere turns is reduced. This checks the tendency for the voltage to rise and maintains a voltage very near that for the intersection P on the curve.

The principle of balancing a signal against a fixed reference is easily extended to cover controls in which the reference varies. In flying shear control, for example, it is necessary to maintain the shear speed proportional to the strip speed. The latter is, in effect, a varying reference and is obtained by means of a tacho-generator driven at a speed dependent on strip speed. This becomes in effect a ratio control since either speed

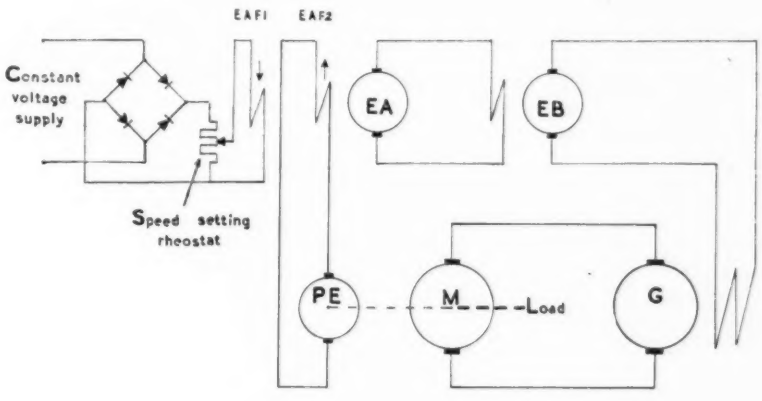


Fig. 3.—Speed control using magnavolt exciter.

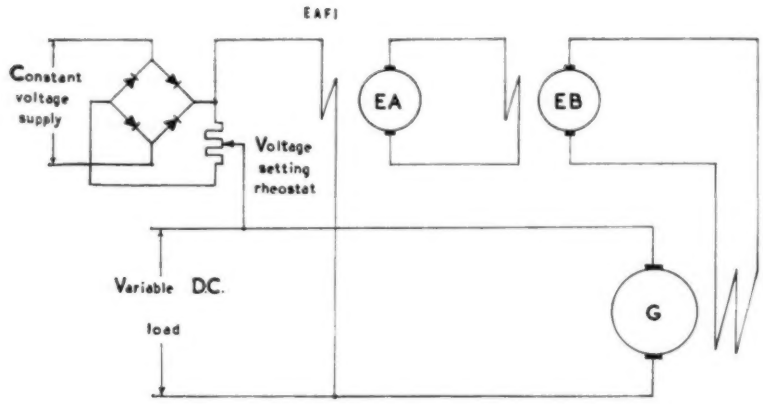


Fig. 4.—Control of continuous voltage by magnavolt exciter.

may vary but the ratio is held constant. The same principle is used in the arc furnace control where the relation between arc voltage and current is controlled, thus providing an indirect control of arc power.

These principles are so flexible in their application that a very wide range of problems can be readily solved by the use of the magnavolt exciter. Two applications are given below in detail to illustrate these principles.

Application of Magnavolt to Coiling Tension Control.

A simplified schematic diagram for a coiler on a reversing mill is shown in Fig. 6. This is interesting in that the booster used is one of the forerunners of the magnavolt.

When coiling steel, non-ferrous strip and many other materials, it is necessary to maintain constant tension. For any given strip speed the horsepower in the strip is constant, and, neglecting the machine and gearbox losses, this leads to constant kW on the machine coupled to the coiling drum. Since a fixed strip speed usually involves a proportionate and fixed voltage across the coiler motor, this motor will carry a constant armature current.

A control scheme for tension, therefore, becomes essentially one in which the coiler motor armature current is regulated to a value proportioned to the required tension.

Before considering the magna volt control circuits it is necessary to describe the function of the booster RB. In the usual single stand or tandem mill each mill motor will have a range of field weakening control to enable the maximum range of products to be rolled. The busbar voltage will be proportional to strip speed only during the voltage control of the mill motor, and it is therefore necessary to modify the voltage applied to the coiler motor so that proportionality to strip speed is maintained.

The correcting voltage is obtained by subtracting a voltage proportional to speed, obtained

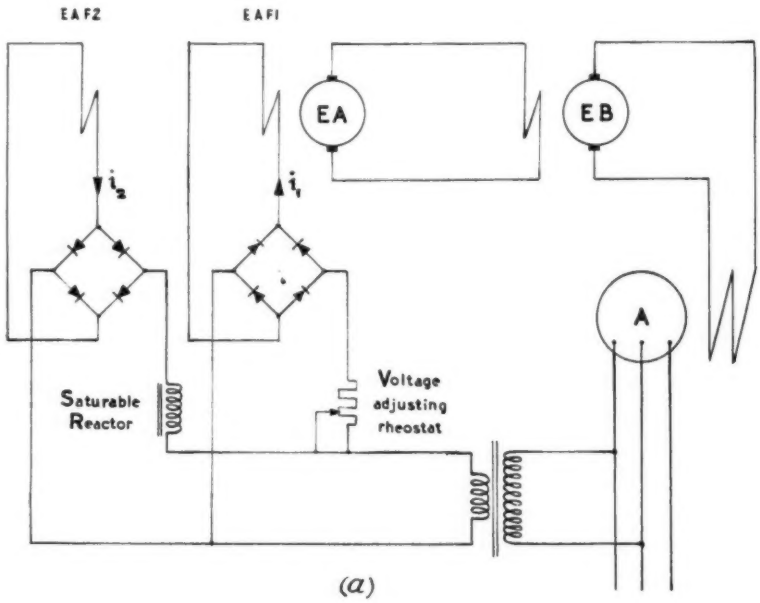
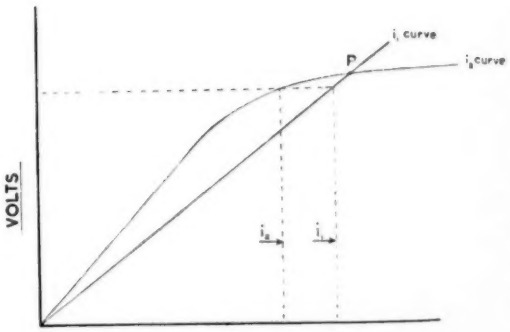


Fig. 5 (a) and (b).—Alternating voltage control using intersecting impedance network.



(6)

from the pilot exciter PE, from the busbar voltage. This is shown in Fig. 7 and by subtracting the voltage between OAB and OB from the busbar volts, the voltage applied to the coiler motor is kept proportional to strip speed in spite of the field weakening of the mill motor.

It will also be noted that the voltage drop in the resistance of booster and reel motor armatures will cause the induced e.m.f. of the reel motor to differ from exact proportionality to strip speed. This is readily overcome by adding a voltage component by means of RBF2 (Fig. 6) to neutralise the resistive voltage drop. Since the current is dependent on the tension, this voltage may be readily set by ganging its controlling rheostat with the tension setting rheostat.

Another booster field is used to make a fractional decrease in the voltage across the coiler motor when the reel is uncoiling. The pilot exciter is effectively coupled to the main rolls and so has a voltage proportional to the peripheral speed of the rolls. When the reel is uncoiling the strip speed will be less than this peripheral speed by an amount depending on the reduction in the main stand. This decrease will evidently vary with the mill speed and so the field RBF4 for draft compensation is fed directly from PE and set by the rheostat RH3. The contactor L energises this field only when the mill is rolling left, i.e., away from this coiler.

The remaining field of RB can be conveniently considered with the corresponding magnavolt field. It will be seen that it is now arranged that the coiler motor induced voltage is proportional to strip speed, irrespective of mill motor field

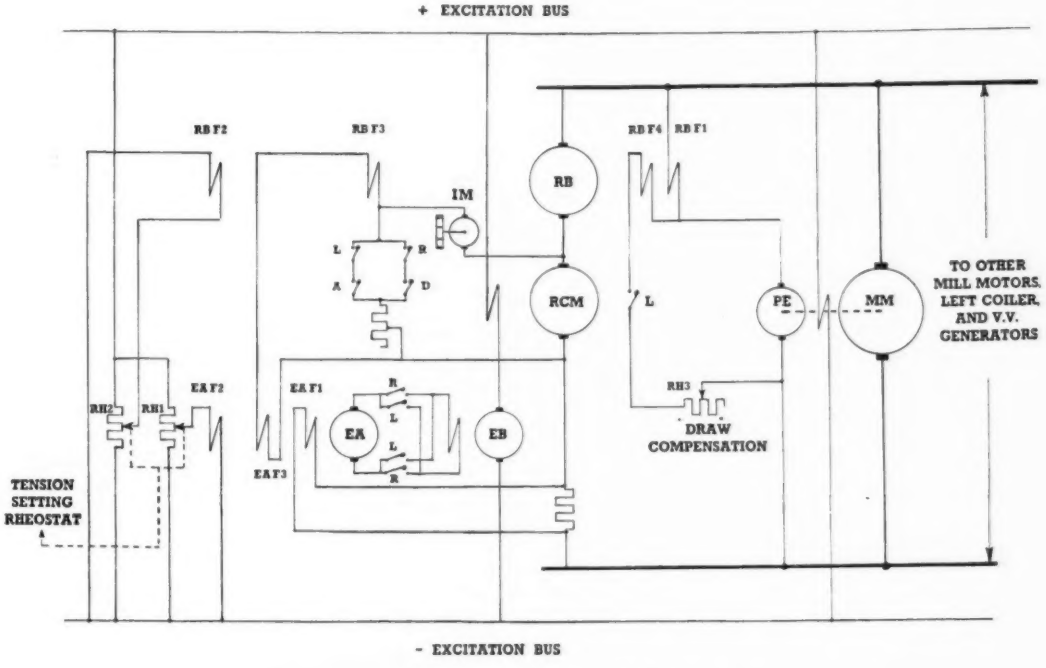


Fig. 6 —Constant tension control for "right" coiler motor.

weakening, draft and voltage drop in the booster and coiler motor armatures. These may be regarded as the predictable variables which have been eliminated so that the task of the control is a straight forward current control in order to maintain the set tension for all values of mill speed, build-up, acceleration and temperature.

The desired value of tension and hence current is set by the rheostat RH1 which controls the current through the reference field of the magnavolt EAF2. The current itself is measured by the field EAF1 which is connected across a shunt in the coiler motor armature circuit. Considering, say coiling, the field EAF2 will tend to cause the magnavolt to buck the constant component of the motor excitation and so weaken the motor field. The field EAF1 will oppose this tendency and neutralise almost all the ampere turns of EAF2. The difference, amplified by the two stages of the magnavolt, will adjust itself until the motor field is just adequate to run the coiler motor at the correct speed and produce the required tension.

As the coil builds up, the diameter increases and the additional torque tends to slow up the coiler motor. This results in a slight increase in armature current which reduces the excess of EAF2 over EAF1 and so strengthens the motor field. Eventually the ampere turns of EAF1 predominate and the magnavolt boosts the constant voltage excitation.

During uncoiling the coiler motor is pulled round by the strip and becomes a generator. At the start of uncoiling the machine is running at the lowest speed and increases speed as the coil is unwound. This leads to a tendency for the armature current to increase and this must be used to decrease the coiler motor field to allow the high speed without excessive current.

This is the opposite to the action during coiling and it is, therefore, necessary to reverse the internal circuit of the magnavolt. The contactors R or L are, therefore, selected according to the direction of rolling, i.e., " right " or " left." When rolling to the right, i.e., right reel coiling, the magnavolt is connected to increase the coiler motor field as the armature current tends to increase. When rolling to the left, the right reel will be uncoiling and the magnavolt will decrease the coiler motor field as the armature current tends to increase.

During acceleration and deceleration a further factor must be taken into account. If no allowance is made for the inertia of the coiler motor, gears and drum, part of the torque which is intended for producing tension will be used for accelerating the rotating parts. In order to overcome this, the effect of the reference field on the magnavolt input is modified during change of speed. This is carried out by the inertia exciter and fields EAF3 and RBF3. These carry the

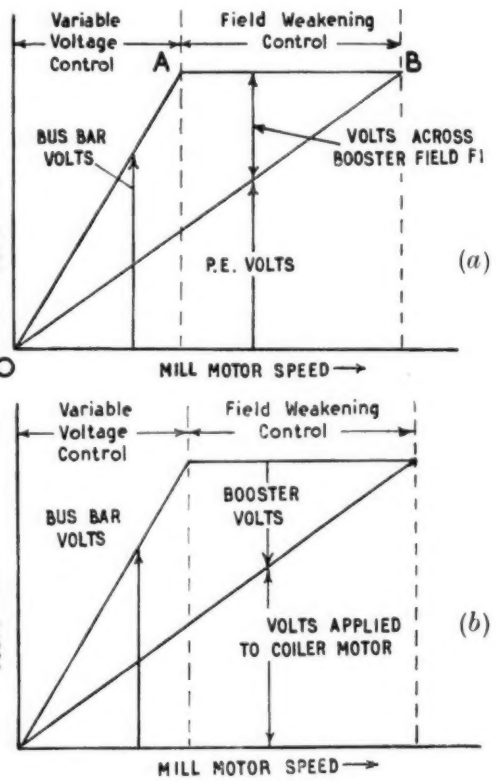


Fig. 7a.—Voltages in the booster field circuit RBF1.
Fig. 7b.—Voltages in the coiler motor armature circuit.

armature current of a small motor running light and connected across the coiler motor armature. When, during acceleration, the voltage across the coiler motor increases, the inertia motor experiences the same increase in voltage and takes an armature current depending on the rate of increase of voltage and its own inertia. By setting the latter by adding a flywheel on its shaft, the inertia motor armature current can be made to correspond to the desired accelerating current for the coiler motor. By using this current to modifiy the effect of the reference field, the magnavolt will regulate to produce the total current required for the desired acceleration and also maintain constant tension.

In the usual coiler system the gear ratio is such that the coiler motor itself is the major inertia to be accelerated. It will be noted, however, that the final speed and, therefore, the rate of acceleration, will differ according to whether the coiler drum is empty or full. To allow for this the inertia compensation fields are shunted

to reduce the compensation when the coiler motor is accelerating to or decelerating from a low speed. This occurs for the right coiler when rolling right and decelerating and when rolling left and accelerating. The contactors R, L, A and D give this effect.

Application of Magnavolt to Dynamometer Control.

A further example of the use of the magnavolt is in the control of a dynamometer for testing internal combustion engines. A simplified schematic diagram is shown in Fig. 8, and it will be noted that the power generated by the dynamometer is fed to an absorption motor AM and returned to the supply by the synchronous machine SM.

In order to make realistic tests of the internal combustion engines to be used in aeroplanes it is necessary to simulate the torque characteristic of a propellor which varies approximately as the square of the speed. Further, in the small equipments for which this scheme is used it is inconvenient to mount any exciters on the dynamometer frame due to the trunnion construction. It is necessary, therefore, to obtain a reference which varies as the square of the speed without actually connecting any machines to the dynamometer.

This is carried out by connecting one armature of a magnavolt across the dynamometer and supplying the corresponding field from the constant voltage exciter. By this means the magnavolt armature is made to follow the dynamometer speed with a small time delay. The second half of the magnavolt has its field fed from a potentiometer RH2, which sets the torque. The output on the armature E1B will therefore vary with the square of speed and the setting of RH2.

The dynamometer field is held constant so that the torque is proportional to the armature current. By comparing the drop in voltage across the shunt R with the square law voltage produced by E1B we have the possibility of controlling the torque of the dynamometer. The difference between the two voltages is used to excite the input stage E2A of another magnavolt and amplified again in the second stage to apply to the absorption motor field. If the speed of the dynamometer increases due to opening the throttle of the engine the current in the main loop will tend to increase very rapidly as dictated by the normal Ward-Leonard characteristic. The increase in current through the resistance R gives a greater excess of the shunt voltage over the voltage from E1B and this increases the excitation of the input of the magnavolt E2A. This is amplified through the magnavolt and applied to the absorption motor, increasing its voltage and so limiting the current in the main loop to that required by the square law.

On most dynamometer equipments it is necessary to employ the dynamometer as a motor in order to measure the losses and to give facilities for running-in. For this purpose the second stage of the magnavolt is supplied from the rheostat RH1 which therefore acts as a speed control for this condition. When the engine is ready to deliver power the ignition is switched on and the dynamometer begins to generate as the throttle is opened. If it is now necessary to change over to propeller law control the torque rheostat RH2 is adjusted until the voltmeter V reads zero. At this point the contactor C can be changed over without shock to the system and thereafter the dynamometer will have a characteristic similar to that of the propeller. If it is necessary to make a change-over in the reverse direction the voltmeter is again brought to zero volts but this time by means of RH1.

In the great majority of equipments the inertia

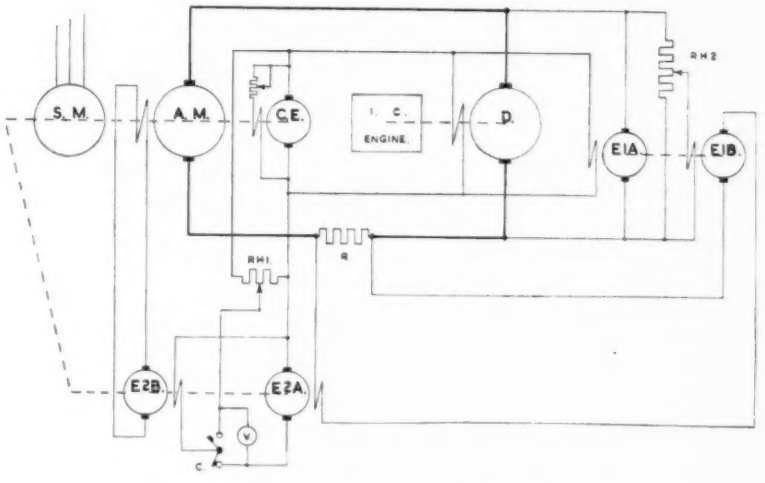


Fig. 8.—Magnavolt control for a small dynamometer equipment testing internal combustion engines.

of the dynamometer is considerably greater than that of the propeller. In acceleration tests, therefore, the engine performance is unduly prejudiced by this large inertia unless some compensation is employed. In this arrangement the magnavolt E1A and E1B always lags a little behind the dynamometer when changes take place. This reduces the reference voltage for acceleration and so gives inherent inertia compensation. The amount of compensation can, if necessary, be adjusted by adding a flywheel to the shaft of the magnavolt.

These examples have been described in some detail to show the extreme flexibility available in applying the magnavolt exciter. It is felt that this exciter gives appropriate solutions to a large range of control problems, not only allowing better control but also giving increased reliability and simpler maintenance.

Type OLX Air-Insulated Metal-Clad Switchgear

A recent addition to the Company's range.

The introduction of the type OLX air-insulated metal-clad circuit-breaker adds to the Company's range of switchgear a unit featuring vertical isolation. This pillar has been designed to meet the demand for equipment of simple design, compact dimensions, certified performance, ease and economy of operation and maintenance, and low first cost.

Application of the OLX unit is, in general, limited only by the range of ratings for which it is available, and although primarily intended for substation duty at 6.6 kV and 11 kV, this circuit-breaker can with advantage be used for such purposes as motor control, industrial distribution, etc. Type OLX switchgear is available for ratings up to 800 amperes, 250 MVA, at 6.6 kV, and 11 kV, these ratings being supported by A.S.T.A. certificates.

An oil-immersed ring-main isolator has been developed for use with this pillar, and used in combination the two units can be employed to meet a wide range of circuit requirements. Typical examples are shown in Fig. 2.

The Circuit-Breaker.

The circuit-breaker is of the cylindrical tank type on the top-plate of which is mounted the operating handle and box-like member containing the low-voltage isolating contacts. These are of the self-aligning cylindrical plug and socket type and any number up to 24 can be provided.

A silicon-aluminium casting forms the top plate of the circuit-breaker, to which are attached the bakelised-paper-insulated terminal bushings. The bushings are attached by means of shrunk-on cast-brass flanges. This simplifies assembly, and offers the advantage that a damaged bushing can be renewed without completely dismantling the circuit-breaker, as is often the case when the bushings are cemented into the top plate.

The contact-actuating levers and links are enclosed within the top plate, and operate the contact bars through a fabricated steel crosshead to which the contacts are attached by insulating lifting arms. The mechanical strength of these arms is such that the circuit-breaker may, for contact setting, etc., be operated dry without damage to the contact system. Tubular guides, containing accelerating springs and buffering, are fitted at each end of the crosshead.

The circuit-breaker is fitted with de-ion grid contacts. This form of arc control device, as is well known, consists of a hollow block comprising plates of insulating material with iron inserts at intervals. This block is bolted to a casting to which are fixed the main and arcing contacts. On opening, the arc is drawn in a narrow, oil-filled slot where the gases liberated, combined with the electro-magnetic effect of the iron plates, extinguish the arc and de-ionise the arc path.

Operating Mechanism.

Type OQG hand operating mechanism is normally fitted to the OLX unit. A feature of the OQG mechanism is that it incorporates making-current and reverse-motion releases.

These releases prevent the circuit-breaker being closed on to a fault. Should an attempt be made to close the circuit-breaker coincident upon a fault developing, the throw-off forces set up when the contacts touch prevent the mechanism latching home, and when this point is reached, the tripping device re-opens the circuit-breaker before any harm can be done.

These also act in the event of the circuit-breaker contacts being closed too slowly. The

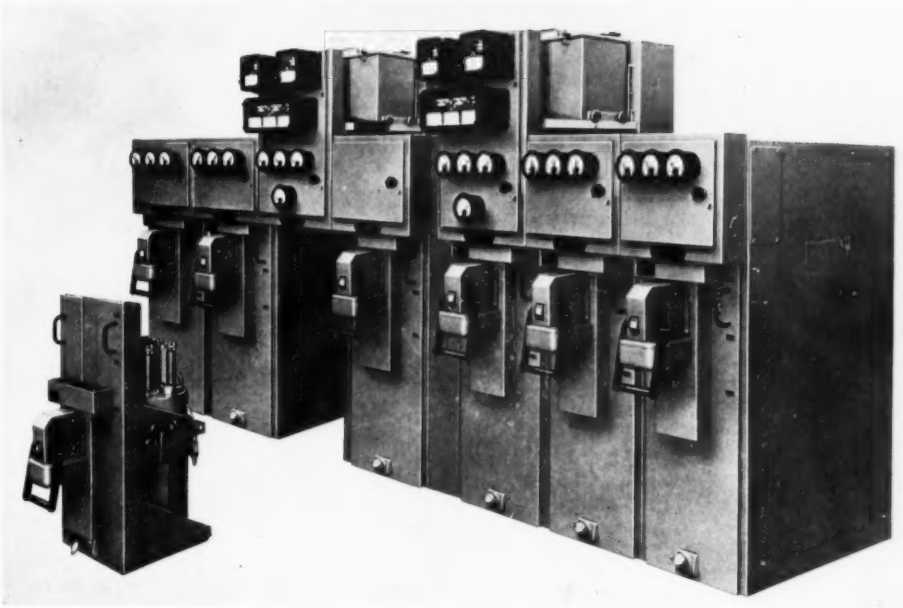


Fig. 1.—Type OLX switchboard comprising two incoming transformer units, bus-section and four outgoing feeders.

effect of closing with insufficient speed is that pre-arcing takes place at the contacts, causing heating, erosion and welding together of contacts. The release is therefore arranged so that if an attempt is made to close the circuit-breaker too slowly the mechanism toggle collapses and allows the circuit-breaker to re-open before the contacts actually touch.

These releases, in addition to affording greater safety to operator and equipment, relieve the mechanism itself of mechanical stresses, such as, for example, those which are transmitted to a mechanism not provided with a making-current release when closed on to a fault. The type OQG operating handle, being lightly stressed, can therefore be made of less massive components than is usual, thus facilitating speed of operation and minimising wear.

The hand-operated version of this mechanism is fitted with a 12 in. lever-type handle, and has a trip-free action. A spring closing mechanism is available for the higher ratings. The usual complement of overcurrent and other releases, up to a maximum of five, can be fitted. The circuit-breaker " ON " " OFF " indicator forms part of the operating mechanism.

Circuit-Breaker Carriage.

This is fabricated of folded and flat steel plate and comprises two main parts, the main carriage and the circuit-breaker supporting cradle.

The circuit-breaker supporting cradle is raised by a vertical screw jack operated by a removable handle. The raising and lowering mechanism is interlocked with the circuit-breaker so that the latter cannot be operated unless it is located in one of the three positions ; " O.C.B. raised," " earth " or " O.C.B. lowered." This prevents the circuit-breaker from being closed when in a partly raised position, such as, for example, when the isolating contacts are only partly engaged. When fully raised and closed, the circuit-breaker cannot be lowered until it has been tripped.

Other interlocks fitted to circuit-breaker and carriage prevent the circuit-breaker from being raised unless the carriage is pushed fully into the housing ; prevent the circuit-breaker from being raised or lowered when in the housing unless it is first " tripped " ; and prevent the circuit-breaker, while in its housing, from being made alive while the tank is removed. A further interlock makes it impossible to withdraw the carriage from the housing unless the circuit-breaker is fully lowered.

The " earth " position is to enable the earthing of busbars or cable to be carried out through the circuit-breaker when required. This is effected by means of extension contacts, the upper ends

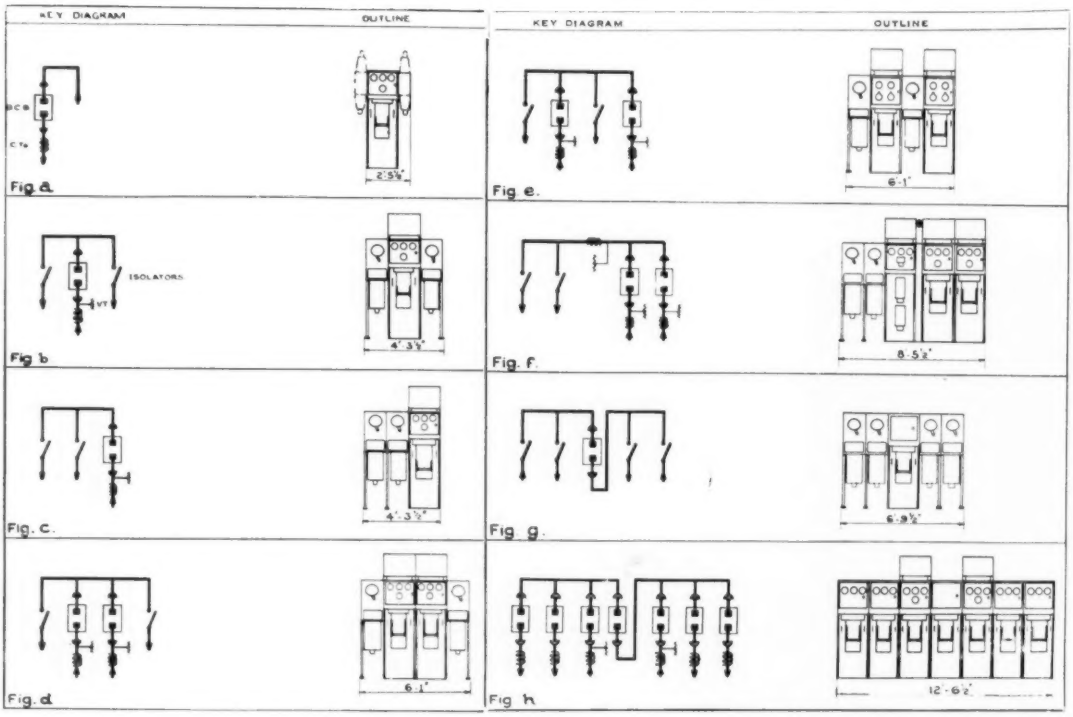


Fig. *a*.—Single oil circuit-breaker pillar with incoming busbar cable box. Internally mounted outgoing cable box, current-transformers and instruments.

Fig. *b*.—Switchboard comprising an incoming oil circuit-breaker pillar and two oil-immersed wing isolators. Oil circuit-breaker unit fitted with current and voltage transformers and instruments.

Fig. *c*.—As Fig. *b*, but with oil-immersed isolator units side-by-side.

Fig. *d*.—Multi-panel switchboard with two oil circuit-breaker pillars controlling alternative incoming supplies, and two outgoing isolator units.

Fig. *e*.—As Fig. *d*, but with an isolator unit interposed between the two incoming pillars.

Fig. *f*.—Switchboard comprising two incoming units (oil circuit-breaker pillars), a busbar metering unit and two outgoing isolator units.

Fig. *g*.—Switchboard comprising two incoming isolator units, two outgoing isolator units and a type OLX bus-section pillar.

Fig. *h*.—Multi-panel switchboard comprising two incoming units, four outgoing units, and a bus-section pillar, all of which are type OLX air-insulated metal-clad pillars.

Fig. 2.—Some typical switchboards based on the type OLX air-insulated metal-clad circuit-breaker.

of which carry cluster-type isolating contacts identical to those fitted to the circuit-breaker bushings. On the side of the circuit it is desired to "earth," the extension contacts are plugged and screwed into the circuit-breaker isolating contacts and the "earth" point comprises a shorting bar which, in turn, plugs into the isolating contacts on the opposite side of the breaker. A copper braid connects the shorting bar to the earthing contact on the circuit-breaker carriage. When the carriage is pushed into the housing and the circuit-breaker raised into the "earth" position, the breaker can be operated in the normal manner to earth the required circuit.

The Fixed Housing.

The fixed portion of the OLX pillar is simple, rigid and light. Ample rigidity is provided by the mode of construction which employs folded steel

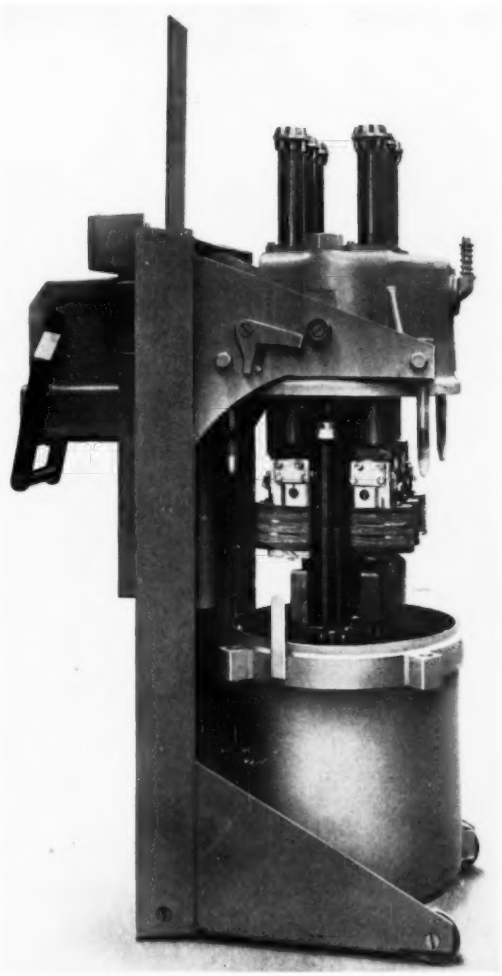


Fig. 3.—Side view of circuit-breaker carriage with tank lowered.

sheets and light gauge angles welded together. The compartments into which the housing is divided are separated by sheet-steel panels.

As will be seen from Fig. 6, the housing is divided into three compartments. The moving carriage is pushed into the front lower compartment. The front upper compartment contains the busbars and fixed members of the isolating contacts between busbars and circuit-breaker. The rear compartment extends to the full height of the housing and is carried forward to embrace the fixed members of the isolating contacts between the circuit-breaker and cable boxes; the circuit-breaker vent pipe is also brought through this compartment to an outlet on top of the housing.

Automatic safety shutters, which cover the isolating-contact apertures, are fitted in the circuit-breaker compartment. These shutters are arranged to open when the circuit-breaker carriage is pushed into the housing, and close when the carriage is withdrawn.

The front upper compartment contains the busbars which are supported on brown glazed porcelain insulators. The busbars are made in unit lengths to simplify extension. No provision is made for compound filling of the busbar chamber, this being an air-insulated unit, but the busbars are insulated throughout their length by phase-coloured plastic sleeving. Connections between circuit-breaker and busbars, and between the circuit-breaker and current-transformers or cable box, are also sleeved.

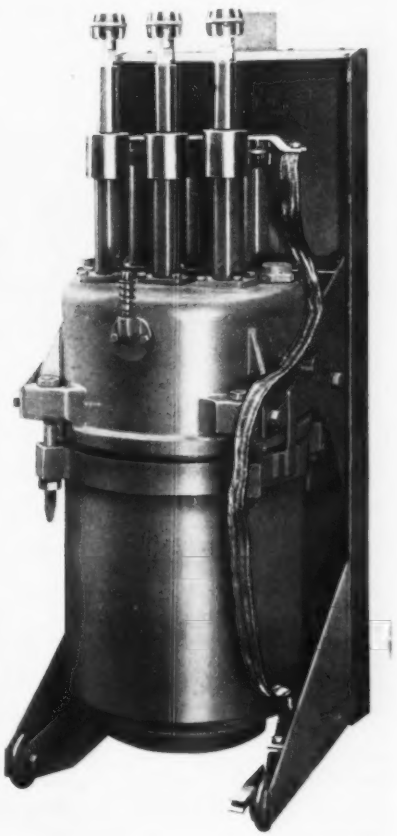


Fig. 4.—Circuit-breaker fitted with contact extensions and connections for cable earthing.

Fig.5.—Operator using circuit-breaker raising and lowering handle.

Space is allowed in the rear compartment of the housing for a double-wound bar-primary type current-transformer per phase. Ample room is available for two trifurcating boxes, the supports for which are bolted to slotted vertical bars. This provides a simple means of adjusting the mounting height of the cable box, or boxes, to suit foundation arrangements.

Ease of access for cabling is usually related to the overall size of the switchgear, so much so that the more compact types of equipment often present the installation engineer with problems which are only overcome with great difficulty. No such problems exist in relation to the type OLX pillar, as the cable boxes are housed in a compartment which extends the full width of the housing and which is fully accessible from the rear or from the inside by removing the appropriate screen.

Attached to and forming part of the front of the housing is a compartment, the lower part of which carries the fixed members of the low-voltage auxiliary contacts. These, as already noted, are engaged by moving contacts fitted to the front of the circuit-breaker carriage. For maintenance and other purposes jumper contacts can be provided. These take the form of two contact blocks connected together, the wiring being protected by flexible conduit.

The body of the compartment previously referred to contains the low-voltage terminal boards, and the hinged door forms a panel on which instruments can be mounted. To cater for various arrangements of instruments and relays, a range of panels is available by which the front of the low-voltage terminal compartment can be extended upwards.

A single- or three-phase oil-filled voltage-transformer can be mounted on top of the housing when required. This is mounted on rails and is isolated horizontally. The voltage-transformer can be connected either on the cable box side or busbar side of the circuit-breaker. In the latter case the overall height is slightly increased.

The main dimensions of the type OLX pillar, without voltage-transformer, are 21½ in. wide, 47 in. deep and 66 in. high. With the voltage-transformer on the cable box side the overall height becomes 87¼ in.; and with the voltage-transformer connected on the busbar side, 91¼ in.

All parts of the pillar are made to very exacting standards so that components from similar units are interchangeable. The operation of adding current—or voltage-transformers to a unit not so fitted, adding a larger instrument panel or an additional cable box, or adding further units to an existing switchboard, can be carried out using standard components, and normally no drilling, welding or other major fitting operation is involved.

Variations on Basic Pillar.

Busbar section and metering units employing standard OLX components are available.

The busbar section pillar comprises a basic

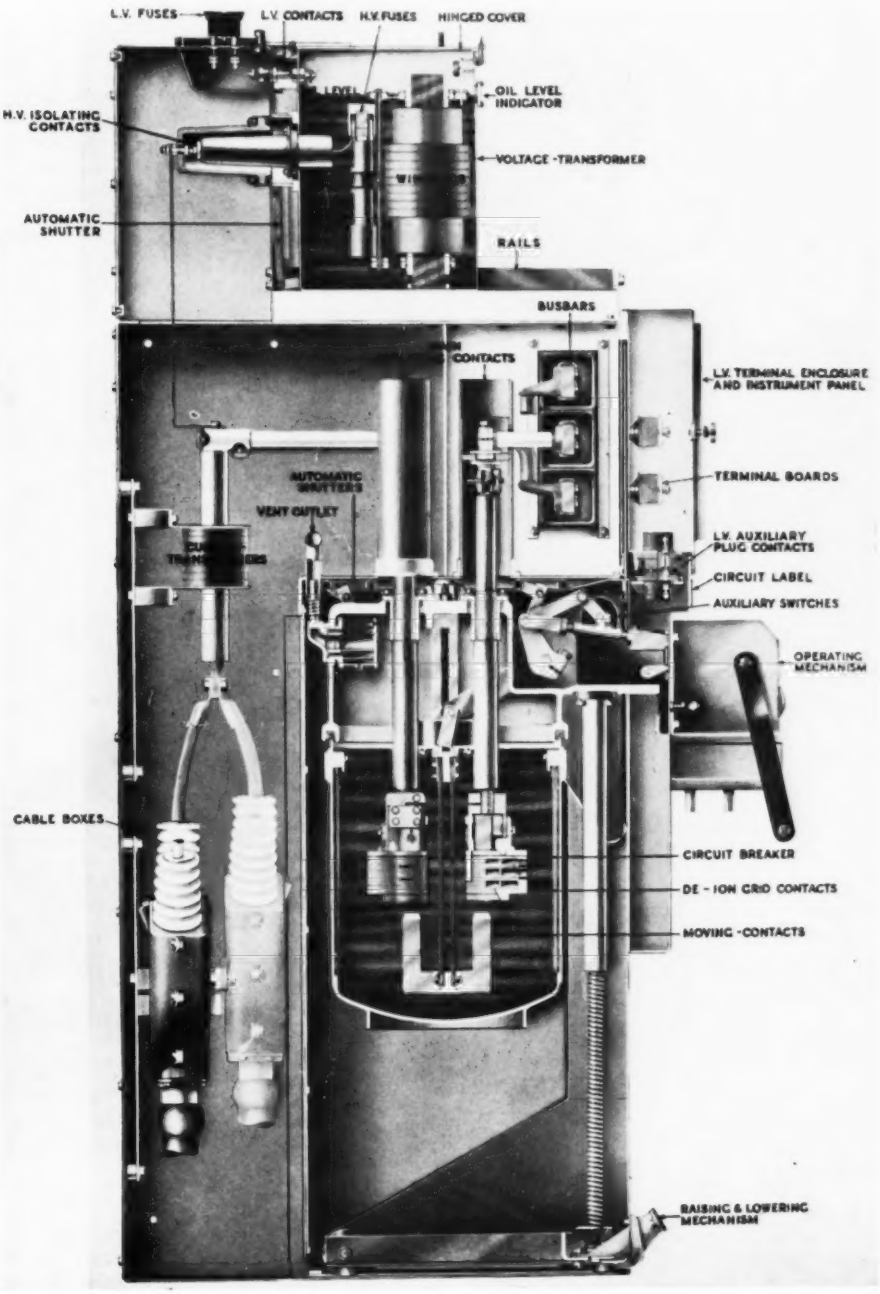


Fig. 6.—Section through type OLX circuit-breaker pillar.

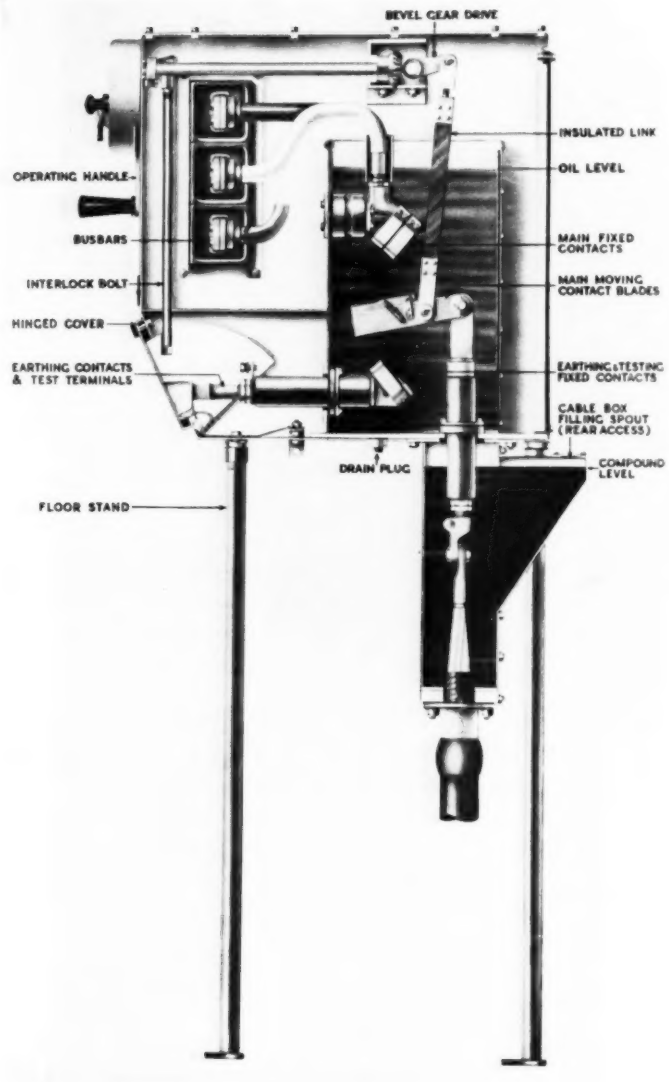


Fig. 7.—Section through type OLX oil-immersed isolating switch.

OLX unit but with a 7 in. wide trunking added to one side.

Five types of metering units are available :—

1. Section metering unit with oil circuit-breaker. This is generally similar to the standard busbar section pillar, but with the addition of voltage- and current-transformers as required.
2. Through-type metering unit. This consists of a housing of similar dimensions to the basic OLX pillar. No circuit-breaker is fitted and the current-transformers are connected solidly into the busbar run. A full-length front panel is fitted in place of the normal withdrawable one, and the standard voltage-transformer is fitted, as before.
3. Metering unit with air-break isolator — feeder type. This incorporates a triple-pole, hand-operated, air-break isolating switch connected on one side to the busbars and, on the other, to a cable box. A normal complement of instrument-transformers can be fitted.
4. Metering unit with air-break isolator — section type. In general this is similar to the feeder type (item 3), but a trunking is fitted to one side giving a total panel width of 28½ in.
5. Metering unit with Barham link switch. This is contained within the overall dimensions of the standard pillar.

Oil-immersed Isolating Switch

The isolating switch is contained in an oil-filled rectangular steel tank. The switch itself is of simple knife type and has a quick-break action between the "on" and "off" positions. A third position, "earth," is provided for cable earthing. Opening a hinged panel at the front of the unit causes the earthing contacts to be disconnected and terminals to be exposed which can be used for injection or other tests on the cables.

The isolating switch is driven by a manually operated handle on the front panel. This operates the blades through bevel gearing, and an interlock is fitted to prevent the hinged panel from being opened until the switch blades are in the "earth" position. The switch cannot then be

moved to the "off" or "on" positions until the hinged panel has been closed.

A large cable box is fitted and can be arranged for filling from either the front or rear of the unit

Complete Substations.

When installed in transformer substations the OLX and isolator units can be used to control the E.H.V. side of the transformer, while the Company's "U35" or "UJ44" distribution fusegear and type OB air-break switchgear can be utilised to control the outgoing supplies from the substation.

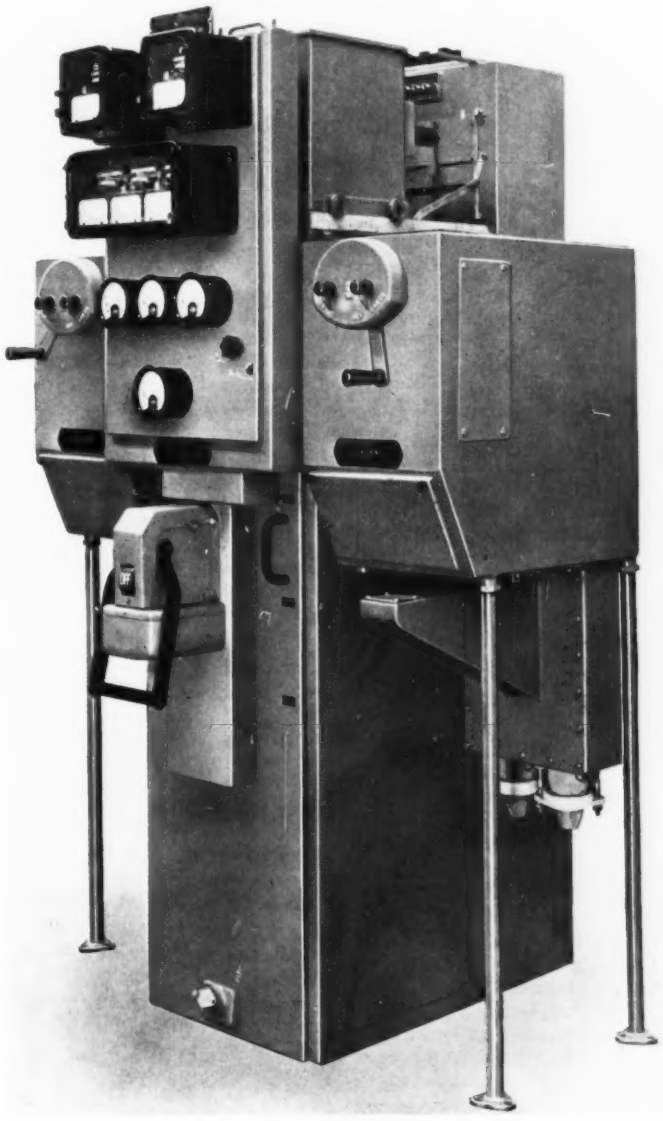


Fig. 8.—OLX unit with voltage-transformer, extended instrument panel and two oil-immersed isolating switches.

"English Electric" Cold Rolling Mill Plant in a Scottish Aluminium Works

By G. R. WILSON, B.Sc., A.M.I.E.E.,
Chief Engineer, Metal Industries Division.

Introduction.

During the recent war the aluminium industry of this country was expanded very considerably in many separate fields, including those manufacturing the metal and working it into usable forms. The English Electric Company contributed extensively in both fields of activity, and this article describes some of the rolling-mill equipment installed at the Falkirk Works of The British Aluminium Co., Ltd.

Before doing so, however, it is worth recording that the largest electrical installation in this country—exclusive of hydro-electric installations—for the manufacture of the virgin metal, was put down in the Port Tennant Works, Swansea. This factory was designed and built for the Ministry of Aircraft Production by The British Aluminium Company, namely, the 41,200 amp., 675 volt, "English Electric" rectifier plant described fully in a previous issue of this Journal.*

The need for factories capable of processing into strip and sheet form the greatly increased amounts of aluminium made available, was partly met by the construction of a complete and fully-integrated factory capable of accepting ingots of the pure metal and its alloys and of working these ingots through several stages up to the despatch of strip and sheet ready for use. This factory was designed and built for the Ministry of Aircraft Production by The British Aluminium Company, and is now owned by the latter. The location is in Falkirk, Scotland, and the choice of this site shows several notable features.

Firstly, there are good electricity, road and rail services in the area, and the nearby Forth-Clyde canal can be used both for transport and as a source of cooling water for certain purposes. Secondly, Falkirk, before the construction of this factory, was largely dependent on a number of ironworks and similar industries, and the introduction of an aluminium industry could be an asset. Thirdly, by building the factory in Scotland, practically all stages of aluminium production would be within its own borders, all owned by The British Aluminium Company. There are ore-treatment plants, two large electrolytic reduction plants (both with extensive "English Electric" hydro-D.C. equipment), and now the hot and cold production and finishing of sheet and strip of many qualities.

Of the large variety of plant installed in the new factory, The English Electric Company supplied not only the complete drives for the five cold strip rolling mills, to be described in the following pages, but also two 500-kW mercury arc rectifier equipments for the general-purposes works D.C. system. In addition most, if not all, of the numerous A.C and D.C. low-tension distribution fuse-switch boards were supplied.

The Five Cold Mills—General.

All five cold strip mills were built by Messrs. W. H. A. Robertson & Co., Ltd., of Bedford, and the first was in production some fifteen months after The English Electric Company received the order for the electric drives.

The five mills incorporate a high degree of operational flexibility. This will be apparent from the accompanying table and the following descriptions, and yet, despite the variety of capability, a surprisingly high degree of interchangeability of components was achieved. The table shows this for the main machines, and it also applies to many of the exciters, other auxiliaries, and control gear. Even on Mill No. 5, which is considerably larger than any of the other four, quite a number of machines, mainly exciters and auxiliaries, and much of the control gear, extend the duplication on the first four mills.

Because of this duplication of components, both mechanical and electrical, each mill is described generally and then many of the component drives are described in greater detail.

Coils of strip in weights of 1,000-2,000 lbs. and thicknesses around $\frac{1}{4}$ in. are obtained from two hot mill units, with widths of about 60 in. and 84 in. Coil-annealing facilities are provided in bays alongside the two mill bays. Extensive local crane arrangements in conjunction with

* June, 1948.

GENERAL DATA ON THE FIVE COLD STRIP MILLS.

Mill No.	1	2	3	4	5
Type of Mill	2-stand 4-high, Reversing Tandem.	2-stand 4-high, Non-Reversing Tandem.	1-stand 2-high, Reversing.	1-stand 2-high, Reversing.	2-stand 4-high, Reversing Tandem.
Mill Roll sizes (work roll diam.) ..	17″	17″	30″	30″	20″
(backing roll diam.) ...	42″	42″	—	—	49″
(roll length)	60″	60″	60″	60″	84″
Top strip speed ft./per min.	295	480	360	360	450
H.P. of each Mill Motor	1,000	1,000	600	600	1,500
Mill Equipment—					
Entry : (*a*) Roll Coiler/Decoiler ...	75 h.p.	75 h.p.	75 h.p.	—	150 h.p.
(*b*) Tension (Drum) Coiler ...	—	—	225 h.p.	225 h.p.	—
Exit: (*a*) Side Trimmer & ScrapCutter	25 h.p.	25 h.p.	10 h.p.	10 h.p.	35 h.p.
(*b*) Tension (Drum) Coiler ...	225 h.p.	225 h.p.	225 h.p.	225 h.p.	550 h.p.
(*c*) Roll Coiler/Decoiler ...	75 h.p.	—	75 h.p.	—	150 h.p.
Main M.G. Set data ... ... (All sets 1,000 r.p.m. with 6,600 volt synchronous motors).	2,200 h.p. motor 2×700 kW generators 2 Reel Boosters	2,200 h.p. motor 2×700 kW generators 2 Reel Boosters	850 h.p. motor 700 kW generator 2 Reel Boosters	850 h.p. motor 700 kW generator 2 Reel Boosters	3,500 h.p. motor 2×1,100 kW generators Reel Booster
Screwdowns (2-motor type) h.p. per motor (D.C.)	30	30	20	20	30

NOTE.—Mills 1 and 2 are arranged electrically so that operation as a 4-stand tandem non-reversing mill is possible, if required.

mobile power-operated trucks give adequate handling around the mills.

It may be thought that aluminium is a rather soft metal and would not require much in the way of h.p. to reduce its thickness by adequate amounts. Pure aluminium, especially when annealed, certainly is soft and mill drives need only have about a quarter the h.p. capacity which a steel mill would require for comparable strip sizes and speeds, but duralumin and other alloys can be much harder and can easily require drive h.p. ratings equal to those proper to a comparable steel mill. The necessity of being able to roll almost any type of alloy has resulted in the present installation having individual mill motors of 600, 1,000 and 1,500 h.p. (R.M.S.), which for strip speeds of 480 ft./min. and below are not small drives.

Mills 1-4 are all in line in one bay, and mill 5 in the next bay. The majority of the electrical equipment is contained in wire-mesh enclosures at the rear of the mills, this arrangement being perfectly satisfactory as the mill atmosphere is very clean. Most of the electrical machinery is, therefore, of the simple open or protected self-ventilated type, though all control gear is enclosed.

The main drives of the five mills form separate 500-volt Ward-Leonard (variable voltage) D.C. systems, this voltage having been selected to give the best design of the machines when these are considered as a whole.

The mill motors, the tension-coiler motors and their main generators are all of the Company's well-known D.C. type, Class CS, specially constructed for rolling-mill service, and are fully compensated so that the suddenly-applied loads and frequent overloads common to rolling-mill operation can be handled readily. The mill motors, one reel motor and the main machines on the M.G. Sets are pedestal-type, while all other machines have conventional ball or roller bearings on end-shields.

Each mill equipment is complete and self-contained, with its own A.C. and D.C. control gear, so that independent working is obtained, but the D.C. bus systems of mills 1 and 2 can be joined for those occasions when 4-stand working is desired. For generation of the necessary D.C. main and control supplies, each equipment includes a main M.-G. set and an exciter set, the former synchronously-driven by a salient-pole motor of class GL or GG, fed from one of two 6.6 kV ring-mains, and the latter driven by a simple low-tension squirrel-cage motor. Synchronous operation of the main sets was selected because of its excellent opportunities for A.C.

system power-factor correction and because of the type of mill.

Constant voltage auxiliary drives are fed from contactor boards connected to the 420-volt A.C. and D.C. systems. The D.C. system is supplied from two 500 kW "English Electric" mercury-arc rectifiers of the pumpless air-cooled steel-bulb type.

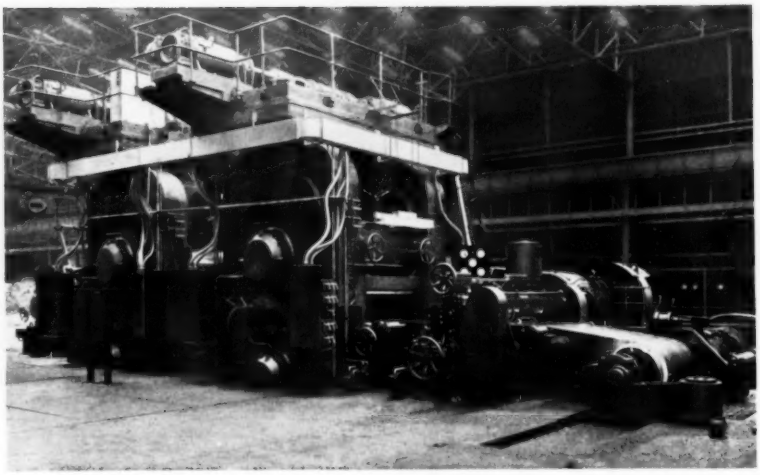


Fig. 1.—General view of No. 1 Mill, 2-stand tandem, reversing, 295 ft. min., with two 1000 h.p. main D.C. motors and a 225 h.p. tension coiler motor. Mill control and indicating cabinets are shown.

Mill No. 1.

The first of the 60 in.-wide mills is a 4-high 2-stand tandem mill, which, along with No. 5 mill, is probably unique in being arranged for reversing working if necessary. A general view of this mill is given in Fig. 1, while Fig. 2 shows the basic circuits. This mill has a maximum top speed of 295 ft./min. on each stand, so that a satisfactory speed-envelope is achieved when working with No. 2 mill as a 4-stand mill, as the latter has a top speed of 480 ft./min.

Each of the two mill motors is rated for 1,000 h.p. continuously, with suitable overload capacity, and carries, in addition to its tacho-generator and overspeed trip, a small direct-coupled pilot exciter developing a reference voltage proportional to mill stand strip speed, for control of voltage on the adjacent coiler or decoiler drives. The mill torques made available by these 1,000 h.p. motors are very high. The torque output from each of the motor gear-boxes has a rated figure of 159,000 lbs.-ft. at full excitation on the motor, and a peak figure of some 400,000 lbs.-ft. These figures are well up to the torque ratings of many larger mill stands for steel and other metals, and reflect the heavy duties expected of this mill. Up to 50 per cent. reduction in thickness is taken on each stand.

The motors are each provided with a speed range by shunt field control of 400/800 r.p.m. at full voltage, the speed having been kept down to give sound motor design and easy acceleration. Shunt field control of each mill motor is reserved, as is usual on cold tandem strip mills, solely for determining the speeds of the two stands relative to one another, to suit the rolling programmes being worked. The mill operators have full control of the motor shunt fields from coarse and vernier rheostats mounted near the mill housings.

Speed control of the mill as a whole, including any coilers and trimmers which may be required to function, is effected by generator voltage control, using two paralleled 700 kW generators, load-sharing between which is achieved by positive and negative series windings and an equaliser bus. This arrangement was chosen so that the No. 2 mill system can be connected to the No. 1 mill system for 4-stand working, and still give adequate generator load-sharing properties.

A side-trimming unit, with separate scrap cutter drive, is inclined between No. 2 stand and the tension coiler, for use on the final pass through the mill.

Mill No. 2.

This mill is very similar to No. 1 mill, the major difference arising from its non-reversing working and from its higher strip speeds. There is therefore only a decoil box at the entry end, and a side trimmer and two coilers at the delivery end. Fig. 3 is a view of the driving side of this mill, and shows the motors and their pilot exciters, and the mill cable trunking, while the motor-generator set, exciter set, and H.T.A.C. control gear are shown in Fig. 4.

Mills Nos. 3 and 4

Each of these two mills is a single-stand 2-high 60 in.-wide reversing unit, with a top speed of 360 ft./min. Fig. 5 shows the driving side of No. 3 mill, which has two tension coilers, two roll coilers and a side-trimmer, while No. 4 is similar but without the two roll coilers.

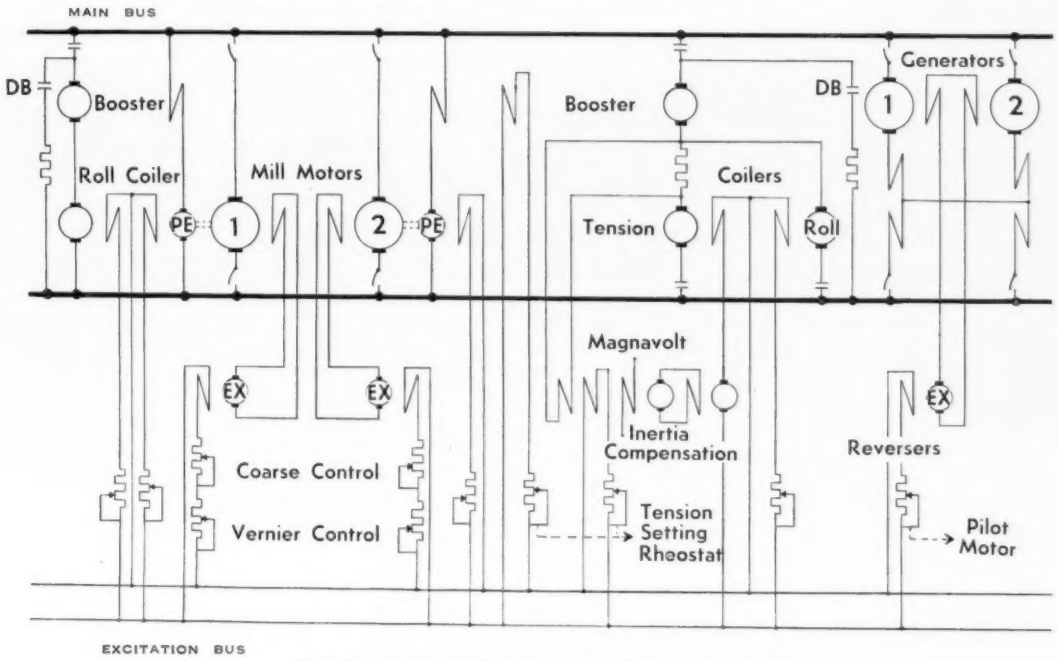


Fig. 2.—Basic circuit diagram for No. 1 tandem Mill.

The mill motors are rated 600 h.p., 800/1,200 r.p.m., and each is equipped with a pilot exciter for coiler voltage control. Mill speed is adjusted by the conventional method of voltage variation followed by motor field weakening. This system is well suited to reversing mill operations since the thicker strips (of consequently shorter length) can be rolled at lower speeds where the greater motor field strength gives greater rolling torque for a given armature current. On each mill the total roll torque has a rated value of 103,000 lbs.-ft. and a peak value of something over 250,000 lbs.-ft. Both these figures are at full motor excitation.

Mill No. 5.

This mill is a 2-stand tandem mill, similar to No. 1 mill in appearance and in being designed for reversing working, but of much larger size and h.p. Whereas mills 1-4 will handle strip up to about 54 in. wide, mill 5 will take strip up to 78 in. wide. The mill size, 20 in. and 49 in. × 84 in. on each stand, makes it one of the world's largest cold mill stands for rolling any metal in strip form and the mill roll torque is proportionately large, being 138,000 lbs.-ft. at the motor rated output of 1,500 h.p. when at full excitation, and being about 350,000 lbs.-ft. at motor peak output.

The strip speed was partly determined by the experience at that time of the highest speeds which it had been found practicable to employ on such strong aluminium alloy strip as the Falkirk factory was designed to produce. In this case the maximum strip speed is 450 ft./min., giving a " figure of merit " for the whole mill of nearly 8 h.p. per ft./min., which compares most favourably with modern steel-strip mills handling a similar width of metal and where the corresponding figure is usually about 7.

General views of this mill and of its electrical equipment, including a 3,500 h.p. motor-generator set, are given in Figs. 6 and 7.

Mill Control.

Each mill stand carries on the operating side two control cabinets and on the driving side two indicating cabinets. All these cabinets are hinged to the mill housing posts, and are of sheet steel construction. The front covers of the operating cabinets are hinged to their bodies to give easy access to the interiors at any time, and the hinging of these cabinets as a whole to the mill housings enables each cabinet to turn through 90 degrees about a vertical axis. This permits individual mill operators to adjust the cabinet positions to suit their own physical build and comfort, and yet allows cabinets to be swung well clear when the mill rolls have to be changed.

Fig. 3.—The two 1,000 h.p. 400/800 r.p.m. driving motors and the pilot exciters on No. 2 Mill.

The control cabinets carry all master switches and push buttons needed for full control of the mill proper and of the screwdown gear, and a number of these controls are duplicated on the several cabinets of a mill to increase the ease of operation. Certain auxiliary drives, such as coil jacks and scrap cutters, are controlled from their own local push button cabinets, while rheostats, essential for mill adjustment from the operating positions, are mounted in suitable locations either on or near the housings.

The remainder of the control gear is accommodated on contactor boards, one per mill, each board being of the floor-mounted cubicle type with hinged doors at front and back. Individual panels carry all contactors, D.C. circuit-breakers, and other devices required for full control of the Ward-Leonard circuits, together with all the gear needed to control the A.C. auxiliary motors and the D.C. screwdown equipment.

Adjustment of mill speed is secured from pairs of cabinet switches, Start/Stop and Slow/Fast. The "Start" position runs the entire mill up to a pre-set slow speed, via a motor-driven rheostat, at which speed strip may be threaded through the mill and on to the selected coiler. The "Slow" and "Fast" positions adjust speed between the limits of the thread speed on the one hand and the maximum speed on the other, while the "Stop" position runs the motorised rheostat right back to its lowest position, after which the generator residual voltage is suppressed and the mill brought to rest. Acceleration between thread speed and top speed normally occurs in about 10 seconds, and deceleration takes place in

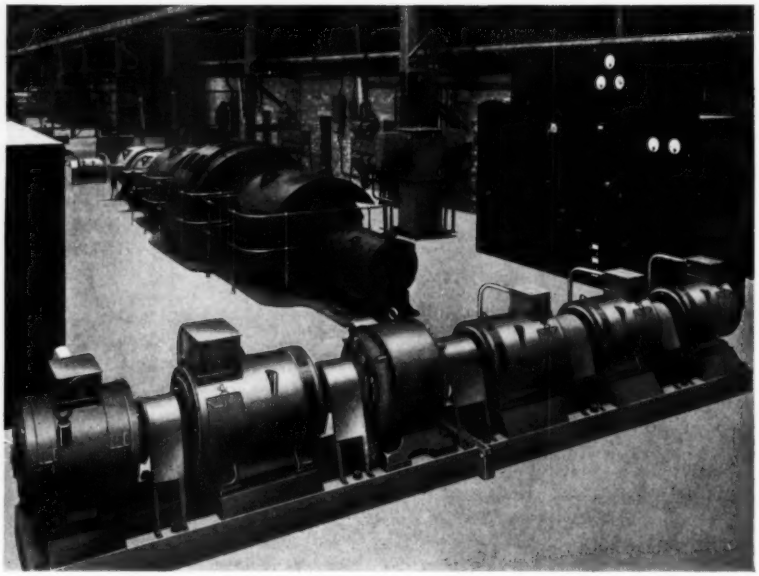


Fig. 4.—2,200 h.p. motor-generator set with its 6.6 kV ring-main and starting equipment, and the 6-machine exciter set, for No. 2 Mill.

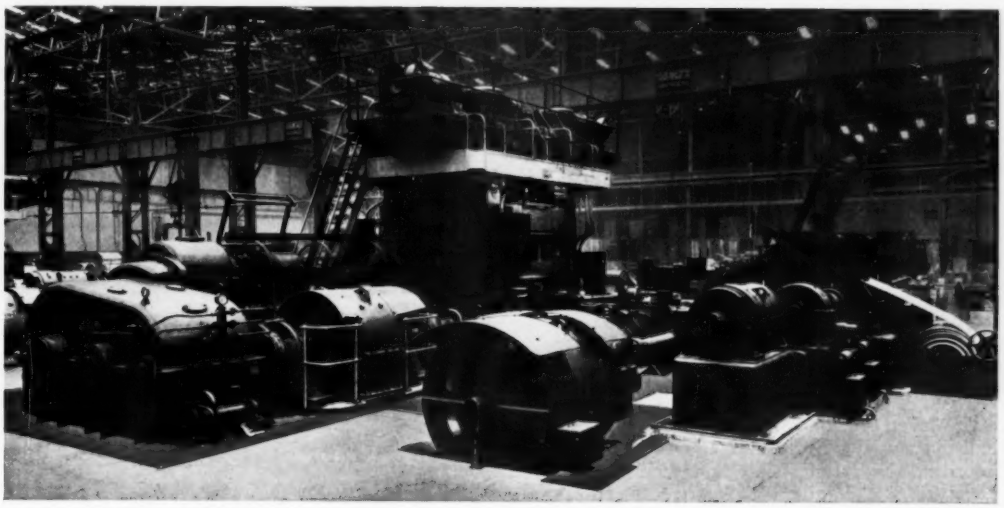


Fig. 5.—The 600 h.p. mill motor, one of the 225 h.p. tension coiler motors, and one of the 75 h.p. roll coiler motors on No. 3 Mill.

a similar time. Emergency stopping facilities are provided, acting on the generator fields to bring the mill to rest in a maximum time of about 3 seconds.

Each generator has its own D.C. circuit-breaker, with automatic overload trips but manually closed and normally left closed. Each tandem-mill motor has an electrically operated breaker for stand on/off control and for protection. These breakers are all of The English Electric Company's well-known OB types, in double-pole units, air-insulated and in cubicles.

Coilers and Decoilers.

The seven tension coiler motors are of Class CS, of 225 h.p. rating each on mills 1-4 and 550 h.p. on mill 5. Those on the tandem mills are for coiling duty only, while those on the single-stand mills are arranged to give both coiling and decoiling tension control. The seven roll coilers are of the three-roll type, with the coils forming above the strip-bending rolls, and are driven by heavy duty steelworks mill-type motors of Class CMR. In the case of the reversing mills, the roll coilers function also as decoilers according to the strip rolling direction selected, and in most cases can be used for power-feeding new strip ends from decoil boxes into the mills. Where a tension coiler and a roll coiler are adjacent to one another on a given mill, the control circuits and equipment are common as far as practicable, and armature selector contactors are included, operated by selector switches at the mill cabinets.

The system of control used on each of the coilers depends on the coiler motor e.m.f. being proportional to the strip speed at that drive. This voltage proportionality is accomplished mainly by a well-tried and patented "English Electric" circuit in which a booster in series with the selected coiler motor is excited both from a mill-driven pilot exciter and from the Ward-Leonard bus, and also by superimposing on this basic control, again via the booster, a further voltage proportional to the main circuit IR-drop.

The main advantages of this circuit are that it inherently gives continuous control from top strip speed through standstill to top strip speed in reverse, without any more contacts than those necessary for on/off functions, and that the coiler motor, if need be on account of special design features or operational requirements, can have an e.m.f. smaller or greater than the bus voltage.

As strip travels more slowly on the ingoing side of a mill than the surface speed of the mill rolls, due to the reduction in gauge (or draft) being effected in that mill stand, a decoiler should work at a proportionately reduced voltage if the tension system is to function correctly at the various mill speeds. This feature is termed draft compensation and is readily introduced by an operator-controlled rheostat in the mill pilot exciter

circuits. On the Falkirk mills drafts of up to 50 per cent. are allowed for.

With coiler motor e.m.f. controlled as indicated above, the remaining control needed consists only of tension coiler motor current control by automatic shunt field adjustment, and manual load control on the roll coilers by simple field trimming rheostats.

The booster also supplies an inching voltage, forward or reverse, to a coiler when required. When a booster is not required to give any voltage, one of its fields is "suicided" to suppress any residual voltage, and this method is also used to assist, very effectively, in bringing a coiler to rest.

Tension Coiler Current Control.

The seven tension coilers develop rated full-load tensions varying between 15,000 and 40,000 lbs. according to strip speed and h.p. rating, and rheostats at the mills set the circuits to operate at any value between about 20 per cent. and 120 per cent. of the appropriate rated tensions. With the usual tension control system used on all large coilers, the motor armature current is virtually proportional to tension, and current-control therefore provides a simple means of maintaining substantially constant tension. On these seven coilers the current-control system uses the Company's magnavolt exciter, a special rapid-response fully-laminated amplifying machine developed over recent years for control applications of this nature. Other articles in this issue describe the magnavolt and its general application to industrial problems.

It is, however, worth recording at this point that the idea of a differential field exciter, such as the magnavolt is in essence, is not by any means new as The English Electric Company has been using such exciters for quickening circuit response for at least thirty years. Typical examples on the Falkirk equipments are the generator and mill motor exciters, which have shunt windings designed to give several times the necessary output voltage and series output-current windings to cancel the surplus ampere-turns due to the shunt field once the output current has built up to the desired value. With this simple arrangement considerable forcing of the main machine fields is achieved.

The field system of the magnavolt includes two windings in opposition to one another, one fed from the operator's tension-setting rheostat and the other from a current-carrying portion of the coiler motor armature circuit. Any unbalance in ampere-turns between these two fields excites the magnavolt which in turn automatically adjusts the coiler motor shunt field system in the corrective direction.

Since the pilot-exciter field can be adjusted for mill work roll diameter variations, such variations have no effect on the coiler tension control. Since the use of the pilot-exciter/booster scheme can eliminate from the coiler motor shunt range any mill motor shunt range, a tension control system of this type requires the coiler motor shunt range to cover only the coil diameter variations (or build-up as it is usually termed). In the present installations, with coil drum diameter of 26 in. and maximum coil size of not more than 39 in., the coiler motors require the relatively low shunt range of $1\frac{1}{2}/1$, and an overall designed range of $1\frac{3}{4}/1$ enables any 225 h.p. coiler motor to work on any of the four smaller mills.

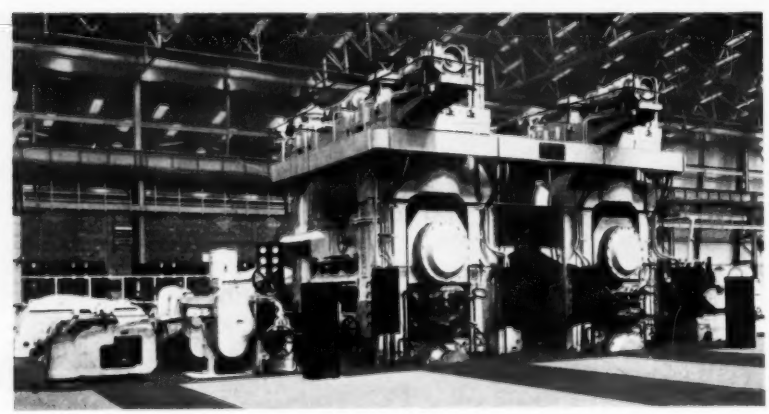


Fig. 6.—General view of No. 5 Mill. This is the largest of the five mills and has two 1,500 h.p. 400/600 r.p.m. mill motors and a 550 h.p. tension coiler motor. The screwdown drives, cable trunking and control cabinets are all shown.

When a coiler is accelerating, the motor current must be increased to provide extra torque over and above the torque which corresponds to the tension in use, and so, to minimise strip tension disturbances during mill speed changes, the control system is biased by the output of an inertia exciter. The latter, a small D.C. machine with a flywheel as its only load, is connected in such a way that the rate of strip speed change is quite closely measured by the

armature current which is then used to bias the magnavolt control system.

Each of the tension coilers has a further feature included, namely, IR-drop compensation. It will be remembered that the control system keeps the coiler voltage proportional to strip speed, but this is only true at all loads if the pilot-exciter/booster circuit gives voltage proportionality at zero coiler current, with compensation for coiler and booster armature circuit IR-drop. Since for any given setting of the operator's tension rheostat the coiler current has a predetermined definite value, there is coupled to this rheostat a second one operating on an extra field on the booster to make the latter inject into the main coiler circuit a voltage compensating for the IR-drop in that circuit. In this way tension changes due to mill speed are eliminated.

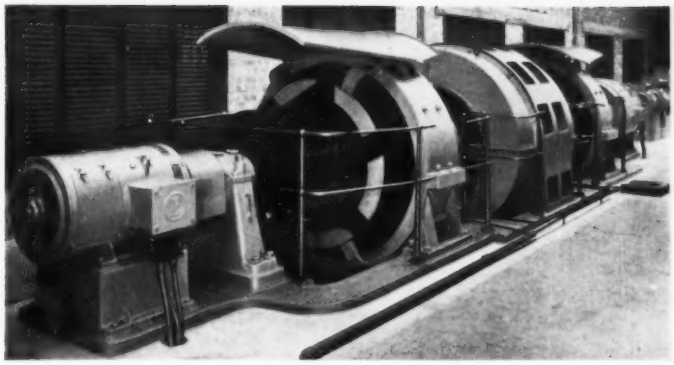


Fig. 7.—The motor-generator set for No. 5 Mill with a 3,500 h.p. 1,000 r.p.m. synchronous motor, two 1,100 kW generators, a booster and an exciter.

When a mill comes to rest with strip already being tensioned, it is desirable to keep some tension on the strip to prevent the coil unwinding and the strip slackening. This tension at standstill, or " stalled " tension, is secured by the very simple means of leaving the IR-drop compensation in circuit when the mill stops. The IR-drop compensation voltage produced by the booster circulates a current in the proper direction through the coiler motor and backwards through the mill motor ; thus these two motors develop small torques in opposite directions, leading to the establishment of a " stalled " strip tension.

It will be noticed from the illustrations that there are no magnetic brakes on the tension or roll coiler drives. Good stopping of these motors, particularly after inching, is obtained by voltage suppression (or " suicide ") on the boosters, which are inside the dynamic braking circuits. In the suicide connection, a field on a booster is connected in reverse across the armature so that any residual voltage in that circuit is appreciably reduced.

The creation of some tension on a strip standstill, with a tension coiler drive, is already catered for by the " stalled tension " circuits already described. This feature, together with the voltage " suicide " show the omission os the brakes to be no detriment. In fact, their omission is beneficial in that drive inertias are considerably reduced.

Roll Coiler Control.

The roll coilers use the voltage/strip-speed proportionality provided by the pilot exciters and boosters, selective line contactors connecting a roll coiler to the circuit in place of a tension coiler on those mills where both occur together. The remainder of the control consists of a hand-operated field-trimming rheostat for each roll coiler motor, to determine the amount of load on the motor. In addition, some of the decoiling roll coilers have reverse current detectors to inform the operators should the strip under certain conditions pull round a decoiling motor. A flashing lamp indicates that the field rheostat requires trimming so that the roll coiler can once again drive the strip towards the mill.

Mill Auxiliary Equipment.

Around the five mills there are quite a number of A.C. and D.C. auxiliary drives and other equipment, mostly small squirrel-cage motors for pumps, coil jacks etc., but including a few more interesting items.

Each mill has a conventional two-motor screwdown drive, contactor-controlled from the 420-volt D.C. supply, and using a pair of steelworks 1-hour rated mill type motors, Class CMR, of 30 h.p. apiece on the tandem mills and 20 h.p. on the single-stand mills. The usual features of single and combined working of one or two motors at a time, with magnetic and dynamic braking, are included, and the equipments are so arranged that when combined working of two motors is required, a magnetic friction clutch is energised to inter-connect mechanically the two drives.

Indication of screwdown position is given electrically at the adjacent mill control cabinets, on cyclometer type counters reading to four decimal places of an inch, and which have Selsyn electrical links back to the screw drives.

Cabling.

Many earlier cold mills have had the mill cables run in conduits all over the mill housings, in a rather unsightly manner, but on the present installations all wiring required on each mill is carried from floor level up a sloping trunking under the mill access ladder and thence in one rectangular trunking around the top of the mill structure. From this trunking short conduits lead off to fixed units such as the screwdown drives, while flexible conduits run down to the hinged control and indication cabinets. Not only is the mill wiring kept well above the inevitable oil-pipes and other oil and water systems, but as all trunkings have removable front covers and contain shelves the wiring is readily exposed for installation and maintenance and the whole arrangement is greatly improved in appearance.

Where the main cable trunking reaches floor level near the foot of each mill ladder, there is a junction box let into the mill floor ; this also has leading into it all conduits from the contactor panels, and from it lead all other conduits to auxiliary devices such as push-button cabinets and tacho-generators, so that the box forms a focal point in the wiring system. This was particularly useful during commissioning, and is of considerable value for routine maintenance, since any circuit is accessible for checking as required.

Conclusion.

These pages describe the equipment as it was originally installed and as it is shown in the illustrations, an equipment of considerable magnitude in that it includes no less than 110 machines totalling almost 30,000 h.p. Recently, however, The British Aluminium Company decided to include on the mills certain additional features and to modify the electrical circuits to cover some improvements which have emerged in the intervening period. These changes are in general not extensive, but will undoubtedly help in gaining still better mill performance and product quality.

In conclusion, acknowledgment is made to The British Aluminium Company for their kindness in agreeing to this article being published.

Pressure Charging the Four-Stroke Diesel Engine
A New Range of Turbo-Blowers

By E. A. SIMONIS, B.Sc., M.R.I., of D. Napier & Son Ltd., Acton

The use of exhaust gas driven turbo-blowers to increase the power output ratings of four-stroke diesel engines, introduced as long ago as 1911, has become accepted practice. Most diesel engine manufacturers now build a standard range of pressure charged engines with a power rating considerably higher than the corresponding range of normally aspirated engines but, until quite recently, there were no turbo-blowers being built in Great Britain, and British diesel engine manufacturers had to obtain each turbo-blower they needed from abroad.

In January, 1949, Messrs. D. Napier & Son, Ltd., of Acton, London, W.3, introduced a series of four turbo-blowers that had been specially designed to meet the demands of the diesel engine industry. The series covered the pressure charging by a single turbo-blower of four-stroke diesel engines with normally aspirated ratings from 180 – 1,400 b.h.p., although engines of larger power could be accommodated by fitting more than one turbo-blower per engine. A wide field of industrial, marine and rail traction engines has therefore been catered for by Napier turbo-blowers and this field includes the entire range of " English Electric " four-stroke diesel engines from the 6 H engine of 220 b.h.p. to the 8 RL engine of 1,144 b.h.p. (normal ratings).

There is more than one system available for pressure charging the four-stroke diesel engine but that most widely in use at the present time and that for which the Napier turbo-blower has been specifically designed, is the system invented by Dr. Büchi where a considerable portion of intake air is utilised to scavenge and cool the cylinders and takes no part in the combustion process. The method of connecting the turbo-blower to the diesel engine is shown diagrammatically in

Fig. 1. There is no mechanical connection whatever between the engine and the turbo-blower, but the engine exhaust gases are led through a turbine before being discharged to atmosphere and the turbine is coupled to a centrifugal air compressor. This compressor draws air from the atmosphere and discharges into the engine intake manifold which is maintained at a positive pressure. The cylinders are thus charged at a positive pressure and will receive a greater weight of air per cycle than if normally aspirated. A correspondingly greater weight of fuel can be burnt leading to increased power.

With no modification to the normally aspirated engine design, the power increase would be approximately proportional to the compressor pressure ratio but the engine would run hot owing to the back pressure imposed on it by the turbine, and the cylinder peak pressures would be high because of the increased air intake pressure. These disadvantages are overcome by incorporating an engine valve timing with a larger valve overlap than used on the normally aspirated engine and by reducing the compression ratio. Fig. 2 shows a typical valve timing diagram of a pressure charged engine from which it will be observed that during 140° of crankshaft rotation, both inlet and exhaust valves are open together and during this period fresh air can blow freely right through the cylinder, with beneficial scavenge action and a pronounced cooling effect on the piston, valves and cylinder head. The exhaust valve however is open for a period of 150° of crankshaft rotation before the inlet valve opens, and during this period the main portion of combustion gases are ejected from the cylinder in a pulse of high pressure gas. The high pressure pulse is followed by a depression in the cylinder which is so timed as to coincide with the inlet valve opening, thus providing ideal conditions for scavenging. Since both inlet and exhaust valves are almost fully open at top dead centre, pockets have to be cut in the piston to clear the valves. The consequent additional clearance space is utilised to drop the compression ratio. By these means it is possible, and in fact has become established practice, to obtain a 50 per cent. increase in engine power with a compressor pressure ratio as low as 1.3 or 1.35 to 1 without substantially increasing the thermal and mechanical loading on the engine above the values accepted for the corresponding normally aspirated engine.

Any increase in compressor pressure ratio above 1.35 : 1 can be utilised further to increase the engine power output but this would normally be accompanied by a hotter engine and higher cylinder pressures with a consequent increased loading on the bearings, connecting rods and other engine parts.

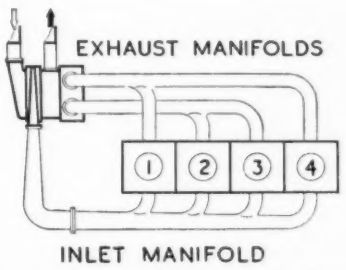


Fig. 1.—The method of connecting a turbo-blower to a diesel engine.

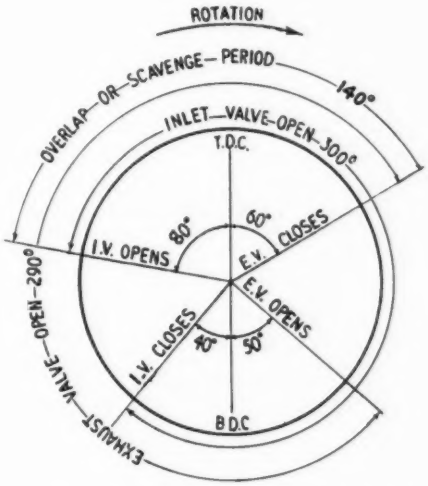


Fig. 2.—Valve timing diagram for pressure charged diesel engine.

With the large valve overlap used on engines pressure charged according to this system a special arrangement of exhaust piping between the engine and the turbine is necessary on multi-cylinder engines, for if two cylinders feeding into a common pipe have their exhaust valves open at the same time, the scavenge of the earlier firing cylinder will be seriously affected by the pulse of exhaust gas released from the later firing cylinder. For this reason it is necessary to lead the exhaust gases into the turbine by a number of separate ducts, ensuring that cylinders exhausting into any particular duct have their firing separated preferably by at least 240° crank angle.

The Napier turbo-blowers are designed for continuous operation at a compressor pressure ratio of 1.5 to 1 ($7\frac{1}{4}$ p.s.i. boost pressure) with a maximum rating for one hour periods of a pressure ratio of 1.6 to 1. A standard Napier turbo-blower has been subjected to an endurance test of 1,000 hours continuous running at the 1.5 pressure ratio rating during which test every 25 hours the speed was increased for one hour to the 1.6 pressure ratio rating. The test was completed in nine weeks during which period the functioning of the unit was entirely satisfactory.

The speed for a 1.5 to 1 pressure ratio is $17\frac{1}{2}$ per cent. above that required for a 1.35 to 1 ratio so that the pressure charging of diesel engines by 50 per cent. is well within the capabilities of the Napier turbo-blowers.

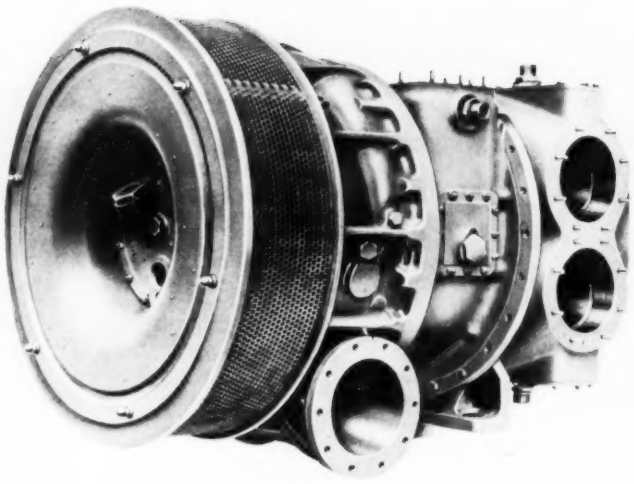


Fig. 3.—An illustration of a TS.200 turbo-blower.

The four turbo-blowers in the Napier range are designated, in increasing order of size, the TS.100, TS.200, TS.300 and TS.400. Particulars of the size, weight and rotational speeds of each type are given in a table which includes an indication of the range of diesel engines for which each type would be suitable.

Although a turbo-blower would appear to be a machine of very simple construction, consisting merely of a gas turbine driving an air compressor, the design of the Napier range of units has presented many interesting problems. With their wide experience of supercharging aircraft engines and designing gas turbine engines, D. Napier & Son, Ltd., were particularly well placed to tackle these problems, being fully conversant with the special mechanical problems involved in the running of high speed machinery and having the requisite background of aerodynamic experience essential for producing high efficiency compressors and turbines. The foremost aims of the Napier design have been high efficiency, long life, simplicity of construction, ease of inspection and maintenance, combined with adaptability to installation on any commercial diesel engine with optimum matching to a particular engine. All four sizes of turbo-blowers are basically similar in design, differences being only in mechanical details.

Description of Napier Turbo-Blowers

Fig. 3 is an illustration of a TS.200 turbo-blower and Fig. 4 shows the parts in an exploded view. Fig. 5 illustrates the components of a TS.100 turbo-blower after completion of the 1,000 hours endurance test.

The turbo-blower consists of a single stage axial flow exhaust gas turbine driving a centrifugal air compressor. The turbine wheel and compressor impeller are mounted on a single steel shaft (*see* Fig. 6) carried in two high speed ball bearings. Each bearing is supported in a resiliently mounted housing with the compressor end bearing arranged to locate the shaft and take any axial thrust, whilst the turbine end bearing slides longitudinally to take up axial growth due to thermal expansion. For ease of access for inspection and replacement, the bearings are mounted outboard of the main rotating components. Each bearing is lubricated separately by its own oil pump which is mounted on the shaft outboard of its bearing. The lubrication of the turbo-blower is entirely independent of that of the diesel engine.

The main body of the turbo-blower is built up of three casings bolted together and each spigotted to the other. These three casings are the turbine outlet casing which forms the support for the whole turbo-blower, the turbine inlet casing which carries the turbine end bearing and its oil pump, and the compressor casing which houses the location bearing and its oil pump. In addition, alternative air inlet casings are available for the compressor, but mechanically these have no function except to lead air into the compressor either from ducting or from the immediately surrounding atmosphere.

The design is such that the three main casings and the air inlet casing can be bolted to each other in any of twelve circumferential positions. The positions of the gas and air inlet and outlet flanges can therefore be set to suit any particular installation on an engine. The turbine outlet casing is

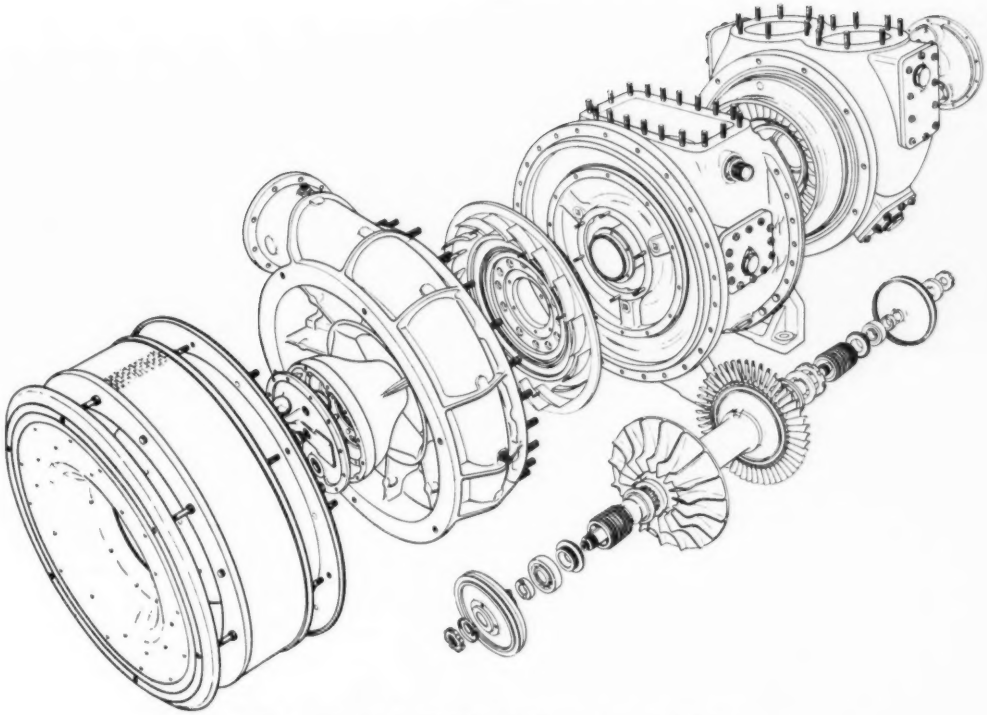


Fig. 4.—Parts of a TS.200 turbo-blower in an exploded view.

supported by two brackets which provide the mounting for the turbo-blower. There are thirteen alternative positions available for these mounting brackets which may be used either as feet or as brackets from which the unit may be hung.

In order to allow for unimpaired scavenge of cylinders with a large valve overlap irrespective of the number of cylinders per engine, three alternative turbine inlet casings are available for each size turbo-blower. The alternative casings are formed with two, three or four gas entries which lead the exhaust gases from the engine cylinders to separate sections of an annular ring of nozzle guide vanes. The exhaust pulses from the cylinders are thus able to be arranged to be kept separate for engines of any number of cylinders until after the turbine nozzles. A two entry casing is used on four and six cylinder engines; the three entry casing suits five and nine cylinder engines, and the four entry casing is required for eight cylinder engines and is also used for seven cylinder engines.

Heat resisting materials are used for all turbine parts to ensure long life at elevated temperatures. All turbine casings are cast in heat resisting Meehanite and are water cooled, the water jacket in the turbine outlet casing being constructed to form a complete barrier against heat passing from the turbine to the compressor. The nozzle vanes are made from Nimonic bar, rolled to a special aerodynamic section. They are held evenly spaced in inner and outer shroud rings with only the inner ring secured to the turbine inlet casing. The outer ring is located sideways but is free to expand outwards, and the provision of a number of slots in the outer ring, cut partially through it alternatively from the back and front edges, enables the nozzle ring assembly to expand without distortion or strain. A shroud ring locates the nozzle outer ring and forms the casing in which the turbine wheel rotates. This shroud is held loosely between the two turbine casings with a loose spigot fit on the inlet casing. In operation, the expansion of the shroud under heat is sufficient to tighten the spigot and prevent movement.

The turbine wheel consists of a disc machined from an austenitic heat resisting steel forging fitted with blades fully machined from similar quality steel bar. The blades are machined to give the design gas inlet and outlet angles at all sections up the blade and are secured to the disc by "fir-tree" serrated roots with a transition fit

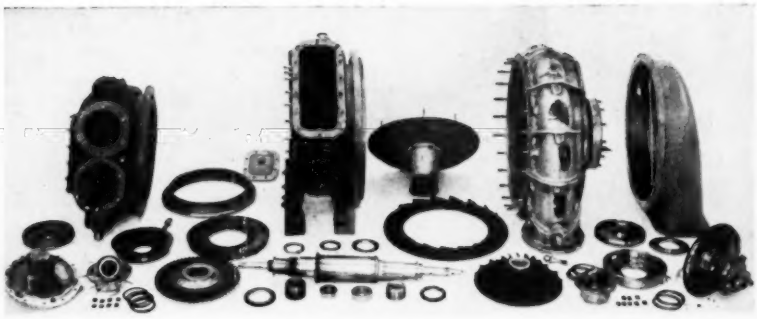


*Fig. 5.—Components of a TS.*100 *turbo-blower after completing* 1,000 *hours endurance test.*

in the serrations. The use of separate blades as opposed to blades integral with the disc has the advantage of assisting in damping out blade vibrations. A small bent-up double tab securing plate locks each blade axially in the disc and allows a blade to be changed without damaging either the blade or the disc.

The centrifugal air compressor is designed to give the flat pressure ratio and high efficiency characteristics typical of all Napier aero-engine superchargers, and a wide range of air mass flows can be accommodated by the compressor at a given impeller speed without substantially affecting either the pressure ratio or the efficiency. It is this quality of the Napier compressor that simplifies the problem of matching a turbo-blower to an engine.

The compressor impeller is of the single entry type with seventeen radial vanes, bent at the leading edges to give correct air incidence angles. The impeller is machined from an aluminium alloy forging with a labyrinth seal turned on its rear face to prevent by-pass of compressed air direct to the turbine outlet. Air leaking through this labyrinth is utilised to cool the shaft and the rear face of the turbine disc.

Air leaving the impeller passes through a die-cast diffuser before entering the delivery volute which is formed in the compressor casing. The diffuser converts the kinetic energy the air has attained in its passage through the impeller into pressure energy at a fairly low velocity in the volute. The delivery volute terminates in a single circular outlet from which air is led to the engine intake manifold. Sea water resisting aluminium alloy is used for all compressor inlet and outlet casings. Each of the alternative air inlet casings is designed with felt lined silencing baffles to suppress the high pitched note associated with a centrifugal compressor. With the ducted type of air inlet casing, air is drawn from a rectangular passage into the eye of the impeller. With the other type, air is drawn from the surrounding atmosphere through a filtering element into the impeller eye. Alternative filtering elements are available in either a corrugated cloth and gauze ruff or an annular box filled with oil-soaked ferrules. When air is ducted in to the compressor from an external source it is advisable to fit an external air filter.

Since the diesel engine on which a turbo-blower is installed may be a stand-by unit or one of a group of power units in a ship or power station, there is a likelihood that the turbo-blower may be stationary for a considerable portion of its life but subjected to vibrations transmitted from other machinery. Some form of protection is therefore necessary to the bearing assemblies in order to prevent incipient failure resulting from "brinelling" of the races during the stand-by period. A special type of resilient bearing mounting (for which a patent has been applied) has therefore been evolved to provide this protection and is now fitted to all turbo-blower bearings. It has been found that apart from the protection against "brinelling", this type of mounting results in smoother running of the turbo-blower accompanied by a drop in bearing temperature and a reduction in noise.

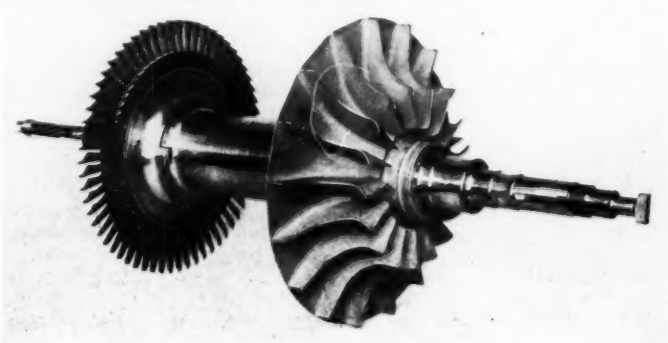


Fig. 6.—Napier turbo-blower rotor.

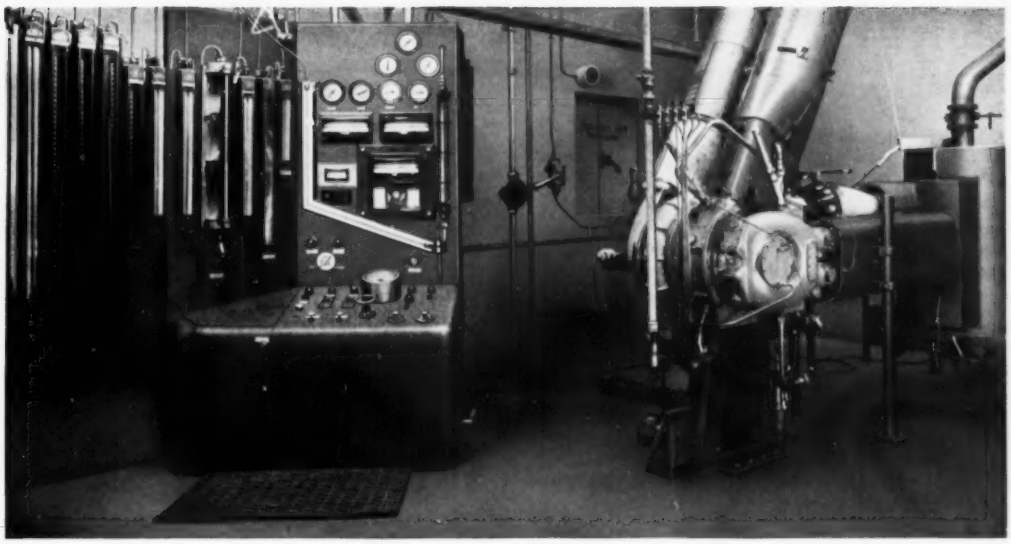


Fig. 7.—A TS.200 turbo-blower on test.

In this type of unit the only components subjected to mechanical wear are the bearings, and therefore, to ensure long life with minimum servicing of a turbo-blower particular attention has been paid to the lubrication of the bearings under all operating conditions. Right from the outset it was decided to devise a lubrication system that was self contained in the unit and entirely independent of the engine's lubrication system. The use of a gear type or other mechanical pump driven from the high speed rotor shaft necessitates gearing and introduces complications and other components subject to mechanical wear. A simple disc type pump has therefore been developed which is incorporated as part of the bearing housing assembly and completely eliminates additional wearing parts and external piping. The pump meets with the requirements of Lloyd's specification for continuous operation at a permanent tilt of 15° in any direction and is designed to work with any good quality engine lubricating oil, being insensitive to changes of viscosity over a wide range of values. A patent has been applied for.

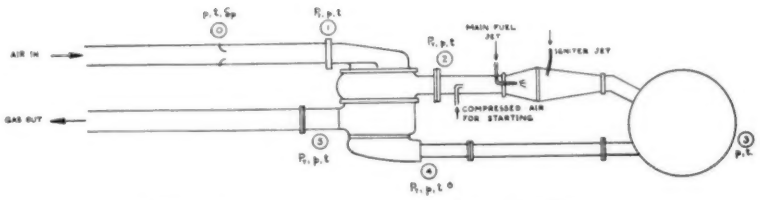
A separate pump is used for each bearing. The pumps are housed in extensions of the turbine inlet and compressor casings which form substantial oil reservoirs. These are filled with oil to a level such that on tilting the unit back at 22.5° all oil is retained in the chamber and none leaks into the turbine or compressor compartments. The pump itself consists of a flanged wheel with the inner portion of the flange turned to a hollow cylindrical surface or lip. The wheel is mounted on the shaft and is of such a size as to dip well into the oil. To prevent any churning up of the oil whilst this comparatively large wheel is rotating at speed, the wheel is completely shrouded. Oil is fed on to the inner lip of the pump wheel through a tube let into the shroud just below the oil surface, is carried round by the wheel and scooped off at the top to run by gravity through passages into the bearing. A metering hole in the inlet tube prevents the circulation of more oil than the bearing requires and a tangential slot is cut in the shroud so that all excess oil is thrown out of the shroud by the windage of the wheel, which consequently runs almost completely dry.

This pump maintains a small but adequate supply of oil to its bearing under a wide range of blower speeds, angles of inclinations and oil viscosities to simulate varying external temperature conditions and even at the highest blower speeds, the oil in the reservoir remains substantially undisturbed. Since the main body of oil remains undisturbed, any sediment in the oil settles at the bottom of the reservoir and never enters the inlet tube to the wheel. However, the wheel is so formed as to act as a centrifugal filter and thus provides an additional safeguard to the bearing.

The seals that prevent oil being sucked into the compressor at the blower end and from passing into the turbine at the other end, are pressurised by air tapped off internally from the compressor delivery volute. At the turbine end this seal

pressurising air is utilised to cool the front face of the turbine disc.

Several important features have been incorporated in the design of the Napier turbo blower to facilitate its dismantling and re-assembly and special precautions have been taken to prevent faulty re-assembly. So that similar parts should not be incorrectly fitted they have been made of different diameters. Where a part has to fit on the shaft a certain way round, the bore has been stepped. Where, for balance reasons, it is essential that a part fits on a shaft in a set position, necessary provision has been made, e.g., the impeller is splined to the shaft with a master spline : the turbine wheel drives the shaft through two dogs, but these dogs are offset from the centre line.



Symbols.

P_T—Total Head Pressure.
p —Static Pressure.
t —Temperature.
δp —Pressure Difference across Nozzle.

Measuring Stations.

0—Air Measuring Nozzle.
1—Compressor Inlet.
2—Compressor Outlet.
3—Manifold Tank.
4—Turbine Inlet.
5—Turbine Outlet.

Fig. 8.—Turbo-blower test rig layout showing measuring stations.

Even though the resilient bearing mountings will allow the shaft to rotate about a centre other than its geometric centre, all the rotating portions of the turbo blower are most carefully balanced. Each shaft, impeller, turbine wheel and oil pump wheel is balanced individually. The complete rotating assembly is then built up and dynamically balanced by removing metal only from two special balancing washers provided. The replacement of an impeller or turbine wheel by similar individually balanced items does not seriously affect the balance of the rotating assembly and damaged parts are capable of being replaced on site without the necessity of rebalancing.

Each oil reservoir is provided with an oil level sight glass, a filling cap and a fine gauze strainer. The oil consumption of turbo-blowers is very low but oil can be topped up with the blower running at any speed. For "Vee" engines, where turbo-blowers are conveniently fitted back-to-back, a special oil level sight glass is provided so that the oil level is not masked.

Testing of Turbo-Blowers

So that intensive running could be carried out to assess the performance of turbo-blowers and to prove the mechanical reliability of their components, a test rig of simple form was designed and two of these rigs were installed at Acton. The rigs are designed on a self-contained principle in which air from the compressor is delivered to the turbine via a combustion chamber in which fuel is burnt. The unit is thus made self-supporting and requires no external source of power to drive it.

The photograph Fig. 7 shows a TS.200 turbo-blower on test and the diagrammatic layout Fig. 8 illustrates the points of instrumentation.

Air is drawn into the compressor from outside the test house through a measuring nozzle and is delivered into the combustion chamber which is fitted with standard fuel burner equipment. The hot gases of combustion pass into a manifold tank from which they can be led through two, three or four ducts into the appropriate turbine inlet casing. After passing through the turbine the gases are exhausted to atmosphere through a stack above the test house. Starting is effected by means of a jet of compressed air from the shop supply line being blown down the combustion chamber which is sufficient to rotate the blower shaft at about 3,000 r.p.m. The igniter jet is switched on, followed by the main fuel supply, when the turbo-blower accelerates to a speed dependent on the quantity of fuel supplied. The entire control is by needle valves in the fuel system. When the compressed air is shut off, the unit becomes entirely self-supporting.

The rig is sufficiently instrumentated to ensure that accurate comparative performance data can be obtained on different units and also the effect of a component design change on a specific unit correctly assessed. No attempt, however, has been made to reproduce the pulsating exhaust of an engine, and consequently the performance figures and overall efficiencies recorded on the rig are only comparative with other figures taken on the rig and are not directly comparable with figures taken on engine tests.

In addition to the main test rigs, a separate rig was designed and manufactured for developing the self-contained lubrication system. In this rig the oil pump, driven by a small air turbine, is mounted in a body which can be tilted in any direction. The oil pump delivery is led on to a measuring vessel or can be fed direct onto the rig

bearings, which are otherwise lubricated from a separate pump. Temperatures are measured in the oil reservoir and the bearings, and means are provided for raising or lowering the temperature of the oil reservoir.

The compressors themselves are tested on a plant that consists of a swinging field electric dynamometer driving the compressor through gearing. Throttle valves in the air inlet and delivery ductings enable the compressors to be fully calibrated by determining the boosts and efficiencies for a range of mass flows at various constant speeds. The adiabatic efficiencies of the compressors are determined from actual power inputs as well as on a temperature basis.

It has already been shown how a four-stroke diesel engine's power output can be increased by 50 per cent. without increasing the mechanical or thermal loading, by coupling the engine to a turbo-blower which is so matched as to run at a compressor pressure ratio of 1.3 or 1.35 to 1 when the engine is on full load. Taking, for example, an engine of 500 b.h.p. normally aspirated rating, by fitting this engine with a Napier TS.200 turbo-blower its rating can be increased to 750 b.h.p. The weight of the TS.200 turbo-blower is approximately 650 lb. and it occupies a space of under 10 cu. ft. Thus the additional 250 engine b.h.p. is obtained for as little as 2.6 lb./b.h.p. and one-twenty-fifth cu. ft. per b.h.p. Even after allowing for the extra weight and space of the manifolds and exhaust ducting, the pressure charged engine can show a very marked reduction in specific weight and specific volume over the normally aspirated engine. Economically the story is similar, the additional horse power being obtainable at a considerably lower cost per b.h.p. than that of the normally aspirated engine. Further, since the extra horse power obtained by pressure charging is obtained with almost no increase in engine mechanical losses, the pressure charged engine is generally more efficient than the normally aspirated engine and consequently has a lower specific fuel consumption.

If the engine will stand higher mechanical stresses and operating temperatures, or could be modified to do so, the turbo blower can be operated at higher speeds and boosts and the engine rating further increased. The pressure charged engine is more favourably placed for an increase in rating than the normally aspirated engine since the air consumption of a constant speed normally aspirated engine is virtually independent of the load but that of the pressure charged engine increases with load. The mixture therefore does not get proportionately as rich with increased load on the pressure charged engine as on the normally aspirated engine. On the other hand, any increase in charge air pressure is accompanied by an increase in temperature to the detriment of the scavenge cooling and the overall thermal efficiency. By the interposition of a water cooled intercooler between the blower and the engine intake manifold, the charge air temperature can be reduced to a value only a little above that of the cooling water, with benefit to both the engine thermal loading and fuel consumption. At least 75 per cent. power increase should be possible on engines pressure charged at a compressor pressure ratio of 1.5 : 1 and fitted with intercoolers. This figure of 75 per cent. by no means represents the limit to which a turbo-blower may be used to increase the power rating of a four-stroke diesel engine. Values over 100 per cent. have already been achieved experimentally. It would however appear to mark the next stage in the development of the commercial pressure charged diesel engine and Napier turbo-blowers are designed with these higher ratings in view.

RANGE OF NAPIER TURBO-BLOWERS

TURBO-BLOWER		TS.100	TS.200	TS.300	TS.400
DIAMETER	inches	18	22	26	32
LENGTH	inches	30	36	45	56
WEIGHT	lbs.	390	650	1,100	1,850
TURBO-BLOWER r.p.m.					
For 50 per cent. pressure charging at 5 p.s.i. boost ...		17,000	13,500	11,000	9,000
Maximum for continuous operation at $7\frac{1}{4}$ p.s.i. boost		20,000	15,750	13,000	10,500
Maximum for one hour periods at $8\frac{1}{2}$ p.s.i. boost ...		21,500	17,000	14,000	11,500
RANGE OF ENGINES SUITED					
Swept volumes—cu. ft. per hour		35,000— 70,000	60,000— 105,000	95,000— 172,000	150,000— 260,000
Normally aspirated power ratings—b.h.p.		180—390	300—585	500—950	800—1,450

The above table contains particulars of the range of Napier turbo-blowers.